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Transpression and Overthrusting in the Minas Basin, Nova Scotia

by

Carlos G. Roselli

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

Department of Earth and Atmospheric Sciences

Edmonton, Alberta

Fall 2003

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Date submitted September 25th, 2003

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled "Transpression and Overthrusting in the Minas Basin, Nova Scotia" submitted by Carlos G. Roselli in partial fulfillment of the requirements for the degree of Master of Science.

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2003 September 25

Abstract

Devonian to Permian successions in the Appalachians of Atlantic Canada record intense deformation in zones related to transform faults active during the assembly of Pangea.

On the south shore of the Minas Basin, Nova Scotia, Late Paleozoic deformation affects the Mississippian Horton and Windsor Groups, lacustrine clastics and evaporites respectively. Structures exposed in cliffs and on wave-cut platforms include reverse faults and tight folds with axial-planar cleavage. Locally, overprinting has led to the development of downward-facing folds. Faults and folds are associated in outcrop-scale flower structures exposed in both cliff and wave-cut-platform view. Low angle thrust faults and oblique strike-slip faults played a role in emplacing Horton Bluff Formation strata over younger strata of the Windsor Group. Thrusting and strike-slip motion were followed by diapirism of Windsor evaporites. This deformation was associated with transpressional motion along the boundary between the Meguma and Avalon terranes of the Appalachians.

To Silvana, who encouraged this effort with unlimited love

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1. Introduction

The Maritimes Basin (Roliff, 1962) is a general term for a basin containing all Late Devonian to Permian rocks in Atlantic Canada (Fig. 1.1). Basin development occurred after Appalachian terrane accretion, represented in the Dunnage, Gander, Avalon, and Meguma zones (Fig. 1.1). The fill of the Maritimes Basin was originally divided into a number of major stratigraphic units (Bell, 1927), of which six are in common use in Nova Scotia (Fountain Lake, Horton, Windsor, Mabou, Cumberland, and Pictou groups). The Maritimes Basin involves several depocentres (Fig. 1.1).

The basin fill is variably deformed. The centre of the basin, from the Bay of Fundy to Western Newfoundland, is intensely deformed, but is bordered by broad undeformed areas. Intense deformation can also be observed in narrow fault-bounded zones, like the former Avalon-Meguma terrane boundary (Fig. 1.1). This zone is variously termed the Cobequid-Chedabucto fault zone (Webb, 1969) or the Minas Geofracture (Keppie, 1982). The Late Paleozoic Horton and Windsor Groups are intensely deformed on the south shore of the Minas Basin, where the area of study includes both the coast and inland outcrops between Summerville and Walton (Fig. 1.2).

This project studies the geometry of deformed rocks and the kinematics of deformation in the Horton Group, with particular emphasis on strike-slip motion and detachments that may have developed within evaporite layers. The possibility that an allochthonous part of the Horton Group crops out in the area is examined.

Brecciation in the Lower Windsor Group and its relationship to any detachment surfaces are also discussed.

1.1. Tectonic setting

1.1.1. Early Paleozoic Zones

The Canadian Appalachians provide an excellent example of an orogen built up through accretion and eventual continental collision. The orogen includes the Appalachian passive continental margin of Laurentia, with peripheral zones being portions of the orogen accreted in Ordovician to Early Devonian time (Fig. 1.1).

The Avalon Zone is the most extensive of Canadian Appalachian zones. It is bordered by major faults. Granite plutonism and mild deformation are consequences of the Precambrian Avalonian Orogeny. These occurrences are viewed as part of a single magmatic-volcanic complex, and a model of a rifted magmatic arc floored by continental basement is accepted (Rast et al., 1976; Strong, 1979; Williams, 1995). Well preserved Upper Precambrian sedimentary and volcanic rocks overlain by Cambrian-Ordovician shale and sandstone characterize the Avalon Zone. The Middle Devonian Acadian Orogeny produced important structures, especially where the Avalon Zone narrows, in Nova Scotia.

The Meguma Zone is characterized by a thick siliciclastic sequence (the Meguma Group) of Late Cambrian to Early Ordovician age. It is a leading example of an Appalachian suspect terrane (Schenk, 1995). It extends through the southern mainland of Nova Scotia and offshore. The boundary between the Meguma and Avalon zones is the Cobequid-Chedabucto Fault Zone (Fig. 1.1).

The earliest interaction among zones was in the Ordovician with accretion of western part of the Dunnage Zone to the Humber (Williams, 1995). The arrival of the Avalon and Meguma zones apparently coincided with important middle Paleozoic tectonism. There is no clear evidence that they were incorporated into the orogen before the Silurian-Devonian (Williams, 1995).

Silurian-Devonian rocks were affected by the Acadian Orogeny, which is dated as Middle to Late Devonian (Williams, 1995) and was followed by terrestrial deposition. The Acadian event produced widespread shearing and faulting that affected most of the orogen.

1.1.2. Late Paleozoic rocks of the Maritimes Basin

The contact between the Pre- and Post-Acadian rocks is unconformable. Post-Acadian development of the Maritimes Basin occurred after terrane accretion. Post-Acadian units are shown in Fig. 1.3.

Intercalated volcanic and sedimentary rocks overlie the Acadian basement at numerous locations across Nova Scotia. These volcanic and sedimentary rocks successions constitute the Fountain Lake Group (Late Devonian to Early Visean) and equivalent strata (Ryan et al., 1991).

The Horton Group overlies the Fountain Lake Group and pre-Acadian basement in angular unconformity. Widespread occurrences of lacustrine clastic rocks of the Horton Group (Tournaisian to Early Visean) imply some connection between the depocentres and suggest a period of accelerated regional subsidence.

Faulting and uplift resulted in widespread erosion prior to the deposition of the Windsor Group. This Carboniferous tectonism was the first of four principal periods of deformation, which affected Upper Paleozoic strata of the Canadian Appalachians (van de Poll et al, 1995).

The thick and extensive carbonates, shales, and evaporites of the overlying Windsor Group, of Middle to Late Visean age (Utting, 1987), probably accumulated in a semi-enclosed basin, remote from a major seaway. In the area of study, the base of the Windsor Group is marked by laminated limestone (Macumber Formation) and abundant carbonate breccias generally designated Pembroke Formation (Weeks, 1948) or Pembroke Breccia. The processes responsible for the Pembroke Breccia have been subject of debate (Clifton, 1967; Giles and Lynch, 1994; Lavoie et al., 1995).

The Mabou Group, Late Visean to Early Namurian in age, contains shallow evaporitic marine to saline continental lacustrine clastics (Ryan et al., 1991). Windsor and Mabou strata were affected by a second period of deformation in the Late Carboniferous, which generated flowage of salt into pillows, ridges, and diapirs (Ruitenberg and McCutcheon, 1982).

The contact between the Mabou Group and the overlying Cumberland Group is unconformable (Moore, 1996). The Cumberland Group, Namurian to Westphalian in age, includes sandstone and shale representing continental fluvial floodplain or braided systems. The Pictou Group, Westphalian to Early Permian in age, consists of continental red beds (Ryan et al., 1991). The third period of deformation consisted of tilting of basement blocks along reactivated basement faults and regional uplift

during the Late Permian (Gibling, 1995). The Late Paleozoic deformation is most intense along the northwest shoreline of the Bay of Fundy in southern New Brunswick, where Carboniferous rocks are involved in thrusts (Gibling, 1995).

1.1.3. Post-Paleozoic rocks

A fourth period of deformation in the Maritimes Basin involved subsidence and uplift beginning in the Late Permian-Early Triassic (Gibling, 1995). This probably ended in the Early Jurassic when Atlantic floor spreading occurred. The Fundy Group, Late Triassic to Early Jurassic in age, consists of continental clastics and basalts with post-volcanic sediments in the upper section. It lies unconformably on most Paleozoic units.

1.2. Previous works

Various parts of the area of study have been previously mapped by the Geological Survey of Canada (Weeks, 1948; Bell, 1960; Boyle, 1957; Stevenson, 1958; Crosby, 1962) and the Nova Scotia Department of Natural Resources (Ferguson, 1983; Giles and Boehner, 1982; notably Moore, 1986, 1993a, 1993b, 1994, 1996; Moore and Ferguson, 1986; Donohoe and Grantham, 1989; Moore et al., 2000).

Fyson (1964) studied the structural geology of the area between Cheverie and Walton (Fig. 1.2) and identified downward-facing folds in Horton Group rocks at Rainy Cove. He differentiated three classes of folds: 1) The main folds, that are

subhorizontal or plunge gently to the southwest, and have axial planes that dip to the northwest. 2) Folds that face downward, show gentle to moderate plunges to the southwest, and have axial surfaces that dip to the south. 3) Folds that plunge steeply to the southwest with axial planes that dip variably to the south. Fyson (1964) inferred that class 2 and 3 developed after class 1 folds, although he was uncertain about the relative timing between class 2 and 3. He proposed regional southeast movements or thrusts of the upper beds to account for the class 1, whereas later veering toward a more southerly direction could have rotated the first generation of folds to recumbent and then downward-facing. In a later work (Fyson, 1967), the main folds (class 1) were interpreted as inclined away from Meguma basement high areas toward troughs. This pattern was inferred to support gravity sliding as a possible mechanism responsible for the class 1 folds (Fyson, 1967).

Boehner (1991) interpreted seismic lines run by Chevron Canada Ltd. from the coast between Tennycape and Minasville, up to 15 km south. He concluded that a low angle, northerly-dipping thrust fault system, the Kennetcook Thrust, transported the Horton Group on top of Windsor Group in the coastal area. He also related small-scale thrust fault occurrences to the larger thrust.

Boehner (1992) analyzed the structural role of Windsor evaporites in the Maritimes Basin and suggested that evaporite-controlled detachment surfaces could have developed in the Shubenacadie and Sydney basins. Examples of extended evaporite diapirs in the Cumberland Basin and Cape Breton Island were also presented.

Lavoie et al. (1995) identified two different breccia units associated with the Macumber Formation in the area of study: 1) A synsedimentary breccia, which is oligomictic and occurs at the base of the Macumber Formation. 2) The Pembroke Breccia, which is a karstic, solution-collapse breccia. The Pembroke breccia occurs at the top of the Macumber Formation, is polymictic and clearly oxidized, and shows irregular distribution (Lavoie et al., 1995).

Johnston (1999) mapped the area from Cheverie Point to Mutton Cove (Cheverie area in Fig. 1.2, Fig. 1.4, Fig. 1.5). The Macumber Formation was observed by Johnston (1999) overlying the Horton Group and the Pembroke Breccia in the Cheverie area was interpreted as a tectonic breccia (Johnston, 1999).

Johnston (1999) mapped the Horton Bluff Formation in the north portion of the Cheverie area as a strongly folded and faulted succession. He observed that folds plunge gently to the southwest and northeast, or are subhorizontal (Fig. 1.5, Fig. 1.6). Axial surfaces are upright or incline steeply. Folds display variable wavelengths, ranging from tens of metres to sub-metre scale (Johnston, 1999). Most of the mapped faults strike northeast-southwest and were interpreted as reverse (Johnston, 1999). Cleavage is penetrative in the shale and for the most part axial planar to the mapped folds (Fig. 1.6).

Moore (1996) and Johnston (1999) interpreted the Cheverie area based on the existing contrast between the north and the south portions (Fig. 1.4). The south portion of the Cheverie area shows a lower degree of deformation. The Cheverie Formation exhibits large-scale, very gentle folds. Moore (1996) and Johnston (1999) postulated a low angle thrust of allochthonous Horton Bluff Formation on top of

autochthonous Cheverie and Lower Windsor Group. Fig. 1.7 shows this interpretation, in which the central portion of the Cheverie area would represent a tectonic window.

Johnston (1999) noted major breccia zones in locations where the Horton Bluff Formation and the Windsor Group evaporites (White Quarry Formation) were inferred to be in structural contact. These breccia zones range from several metres to about 100 m in width along the cliff section, and they consist of angular clasts of Horton Bluff shale and a black clay matrix cut by pink gypsum veins. Johnston (1999) interpreted these outcrops as related to structural emplacement of allochthonous Horton rocks or post-tectonic solution-collapse of Windsor evaporite.

Kontak (2000) described a diabase dike intruding folded Horton Bluff strata in the Cheverie area. Diabase intrusions were observed to truncate the tectonic fabric of Horton shale (Johnston, 1999; Kontak, 2000) and have been dated ($^{40}Ar/^{39}Ar$ whole rock) at 315 ± 4 Ma (Late Namurian-Early Westphalian).

Devon Canada Corporation ran eight seismic lines in 2000 and drilled oil well Cheverie-01 in 2001 (Chapter 4). Seismic data, core samples, core logs, and drill hole cross sections were generously made available for this study and are analyzed in Chapter 4.

1.3. Objective of this project

This project studies three main aspects of the deformation in the area from Summerville to Walton (Fig. 1.2): 1) The geometry of deformation of both Horton

and Windsor groups. 2) The relative timing of faults and folds in the Horton Group. 3) The bulk strain in the Horton Group, with particular emphasis on the link between strike-slip motion and detachments that could have developed within the evaporites of the Windsor Group.

The possibility that an allochthonous part of the Horton Group crops out on the coast and adjacent areas is examined. The role of Windsor evaporites is analyzed, since detachment surfaces and salt diapirs have been interpreted in the area. The origin of the Pembroke Breccia in the lower Windsor Group is also here considered, as it is relevant to the deformation history.

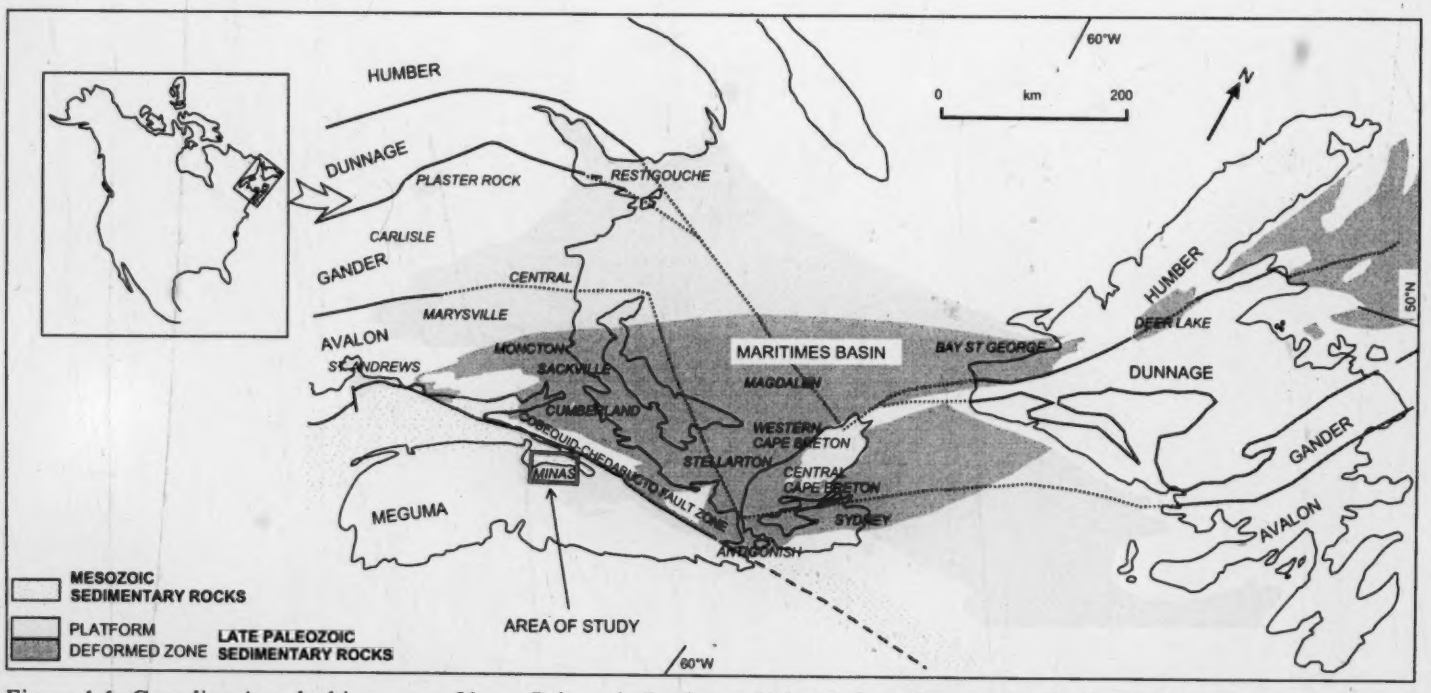


Figure 1.1: Canadian Appalachian zones, Upper Paleozoic Rocks, and Mesozoic sedimentary rock distribution. Depocentres involved in the Maritimes Basin appear in italics. The area of study is the south shore of the Minas Basin.

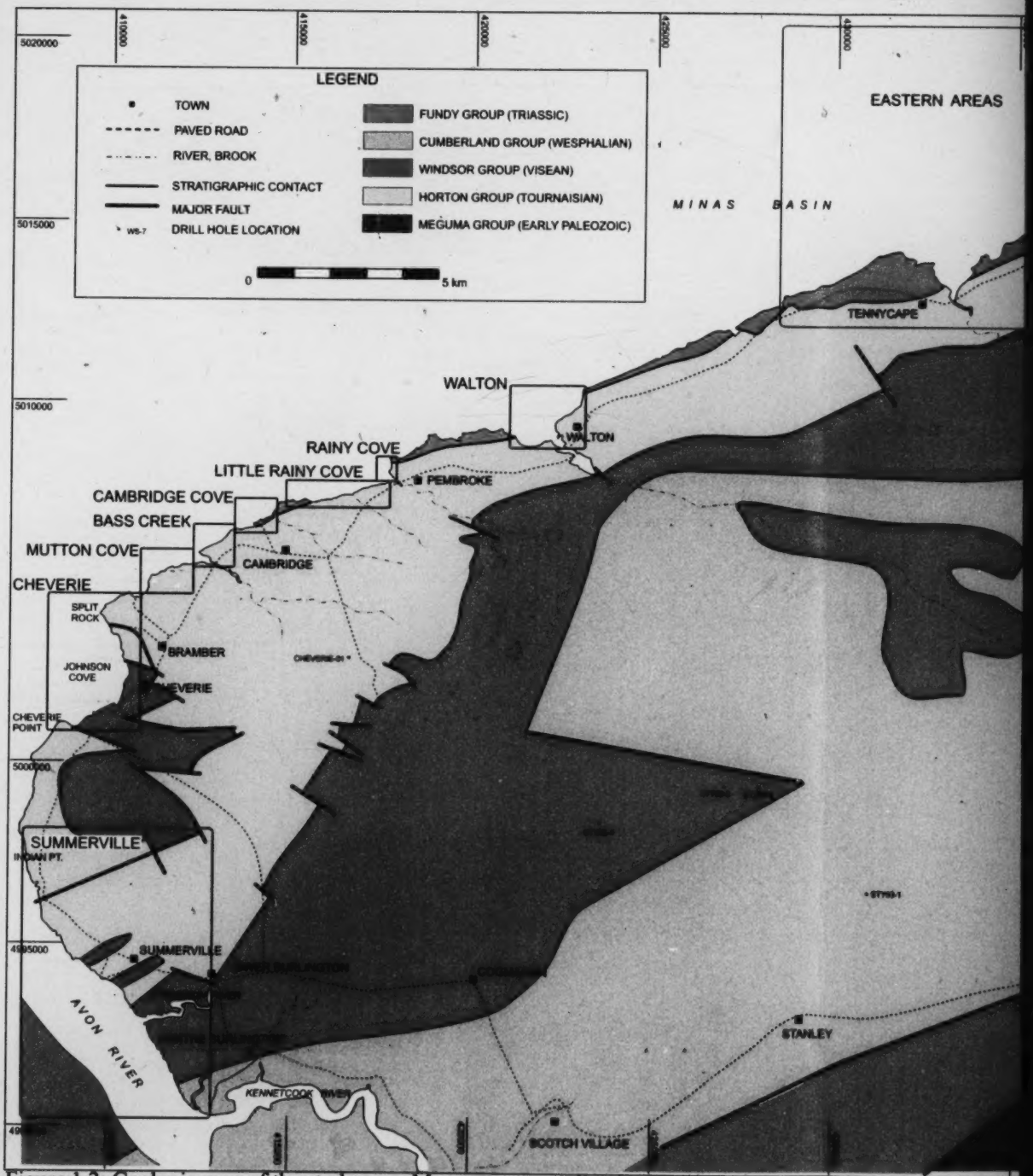


Figure 1.2: Geologic map of the study area. Map areas are outlined in rectangles: Summerville, Cheverie, Mut
Inland geologic contacts were taken from Crosby (1962), Donohoe and Grantham (1989), and Moore et al. (20

rville, Cheverie, Mutton Cove, Cambridge Cove, Little Rainy Cove, Rainy Cove, Walton, and Eastern Areas.
and Moore et al. (2000).

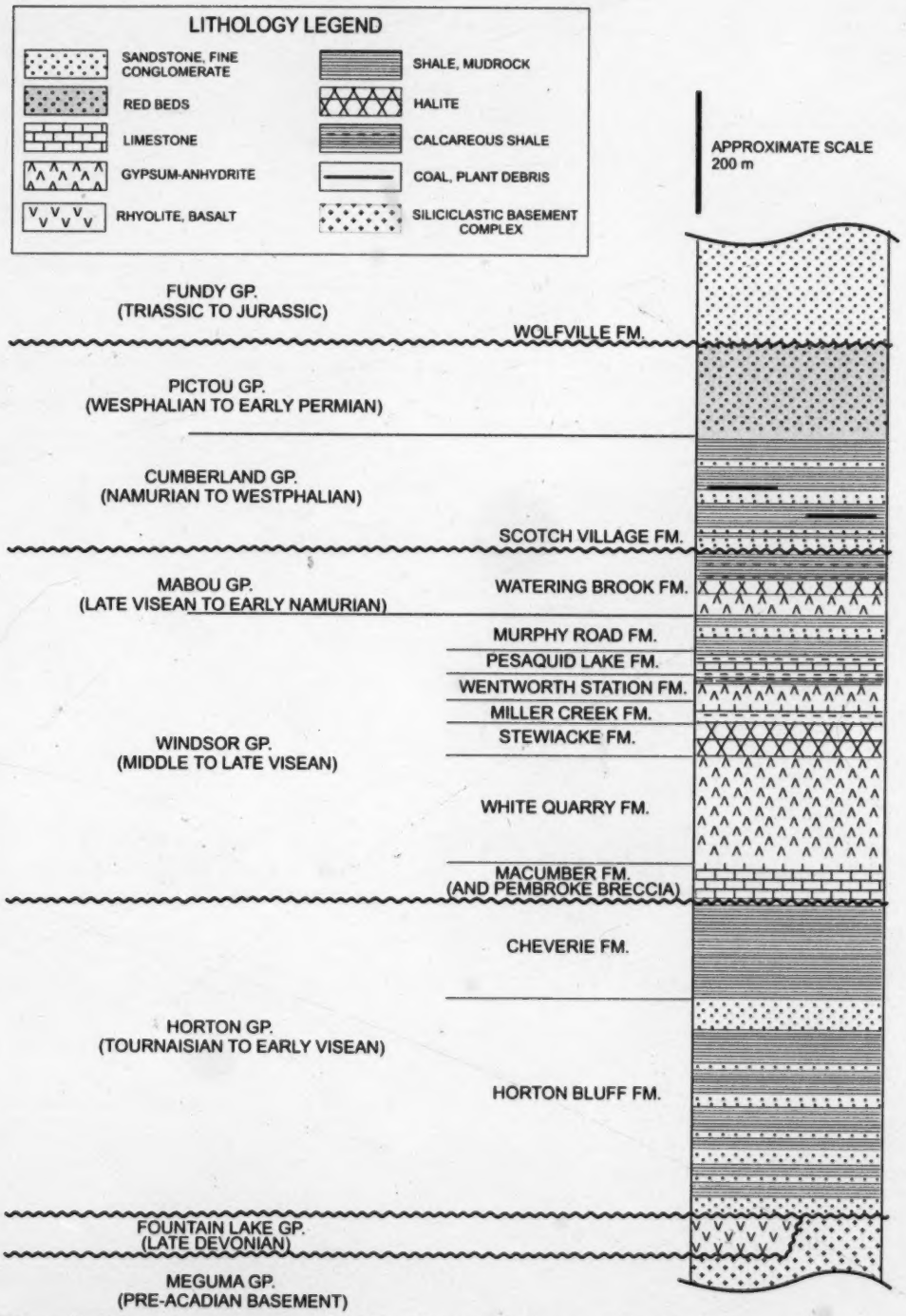


Figure 1.3: Stratigraphic column of Post-Acadian Groups in the Maritimes and Formations in the area of study.

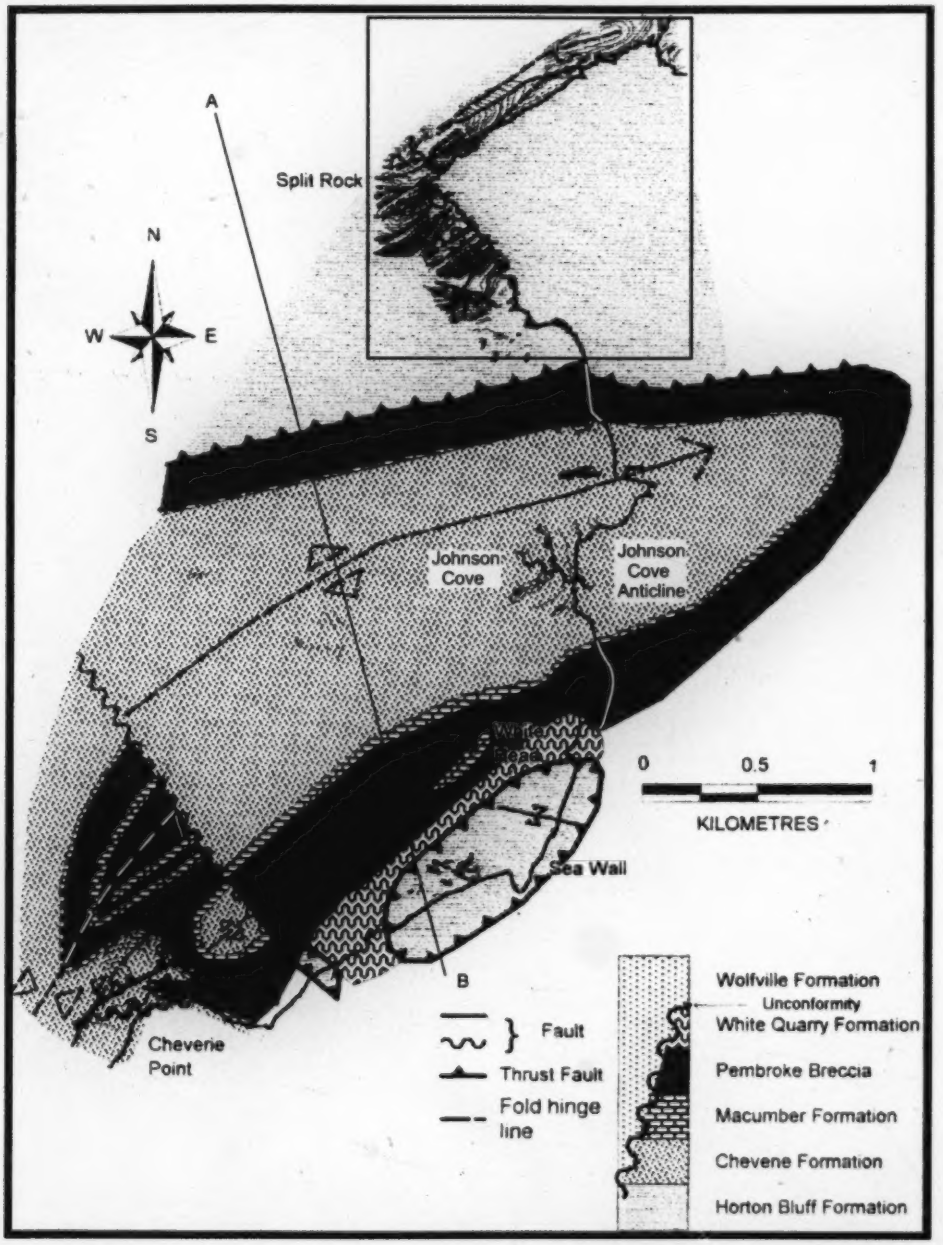
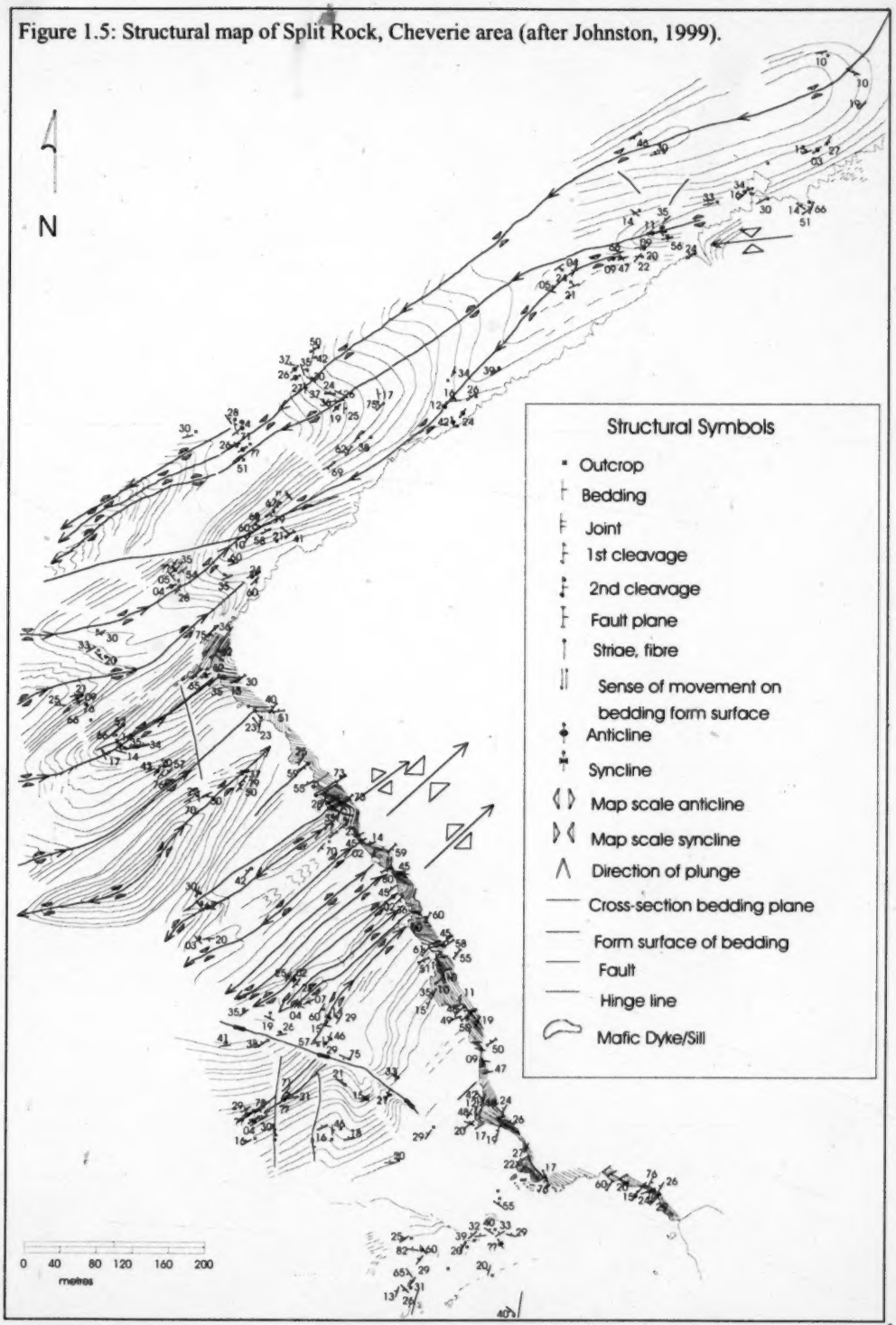


Figure 1.4: Geologic map of the Cheverie area (after Johnston, 1999) in the South shore of the Minas Basin (Fig. 1.2). The rectangular area including Split Rock represents the detailed map in Figure 1.5. Interpretive cross-section AB is offered in Figure 1.7.

Figure 1.5: Structural map of Split Rock, Cheverie area (after Johnston, 1999).



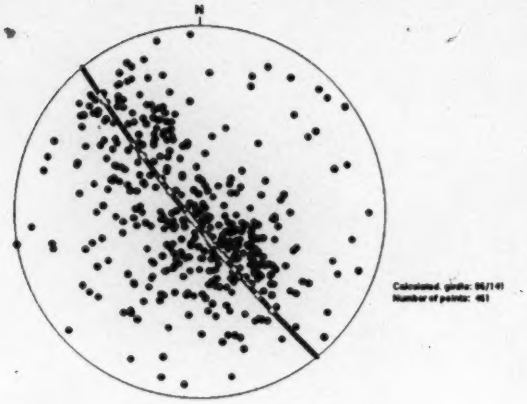
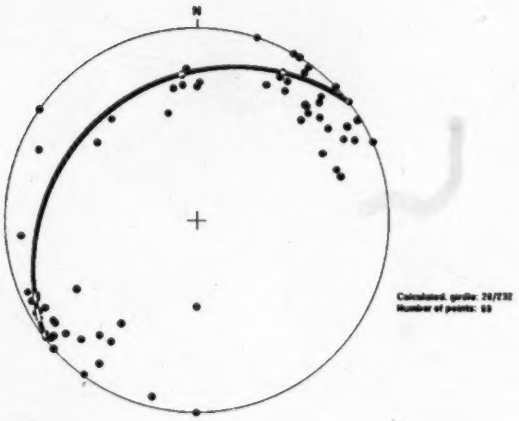
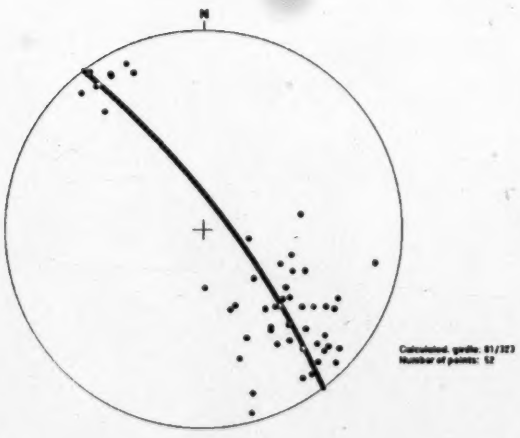


Figure 1.6: Stereographic projections, Cheverie area.

A) Poles to bedding (dots) and girdle distribution (great circle). The highest density cluster lies in the southeast quadrant, dipping near horizontal. A second cluster lies in the northwest quadrant dipping roughly 45°.



B) Fold hinges (dots) and mean axial plane (great circle).



C) Poles to cleavage planes (dots). Cleavage plane dips vary between southeast to northwest. This could be due to cleavage refraction between fine sandstones and shales.

(Stereographic projections A, B, and C, after Johnston, 1999)

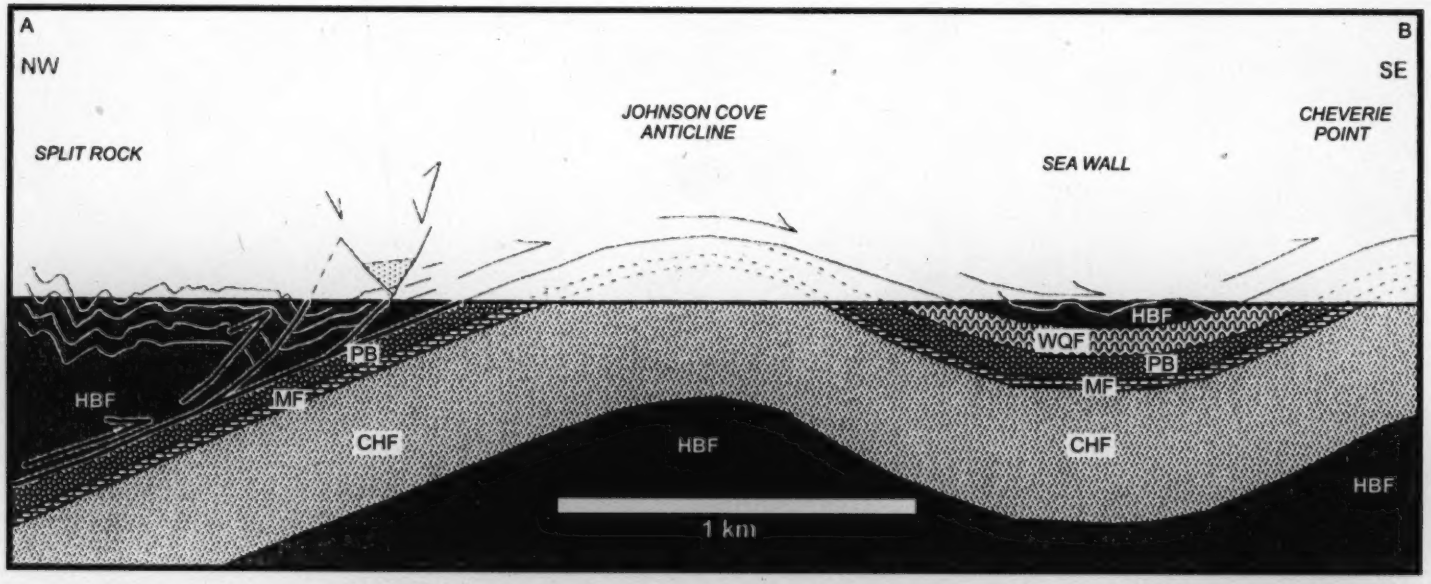


Figure 1.7: Interpretive cross section (AB in Figure 1.4) showing thrusted Horton rocks on top of Windsor evaporite. In this interpretation, the Johnson Cove anticline represents a tectonic window in the area between Split Rock and Cheverie Point. HBF: Horton Bluff Formation; CHF: Cheverie Formation; MF: Macumber Formation; PB: Pembroke Breccia; WQF: White Quarry Formation (modified after Johnston, 1999).

2. Stratigraphy

This chapter describes the rock units in the study area and presents competing hypotheses for the stratigraphic interpretation of the clastic rocks mapped on the coast as Horton Group by previous authors. The origin of breccias in the Lower Windsor Group is also discussed. The stratigraphy of the Horton, Windsor, Cumberland, and Fundy groups are discussed and constrained by field observations.

2.1. Horton Group

The Horton Group (Dawson, 1873; Bell, 1927) of Tournaisian age, locally Late Devonian to Early Visean, overlies the pre-Acadian basement in angular unconformity (Fig. 1.3). It consists of: grey to black shale; grey fine to coarse-grained sandstone; locally feldspathic to quartzose conglomerate; and minor thin limestone interbeds (Moore, 1996). Two Formations have been recognized, the Horton Bluff Formation, in the lower part of the Horton Group, and the Cheverie Formation, which overlies the Horton Bluff Formation (Bell, 1927).

The Horton Group has been mapped in detail in the coast from Summerville to Lower Selma (Fig. 1.2). In general, outcrops are continuous and well-exposed. The Horton Group has been mapped and differentiated into Horton Bluff and Cheverie formations.

2.1.1. Horton Bluff Formation

The Horton Bluff Formation is clearly recognizable in the field as a succession of grey to black mudrock that includes shale, siltstone, grey fine to coarse-grained sandstone. Aneimites acadica and Lepidodendropsis corrugata are the most common plant species in the Horton Bluff Formation (Bell, 1960). Total thickness of the Horton Bluff Formation ranges from 350 m to more than 525 m, and may exceed 1000 m in the central part of the basin (Moore, 1996). The depositional environment of the Horton Bluff Formation has been interpreted as fluviolacustrine (Bell, 1960; Moore, 1986; Martel, 1990).

The Horton Bluff Formation was divided into lower, middle, and upper members, following the criterion of Moore (1986, 1996). The lower member is the coarsest member of the Horton Bluff Formation; it consists of grey, poorly sorted, planar to cross-stratified conglomerate, in fining up sequences (Ferguson, 1983). The lower member has not been identified in the study area.

The middle member is a fine-grained succession of grey to black fissile shale, subordinate fine sandstone, and rare green mudstone. Moore (1996) identified a shale subunit of the middle member, characterized by a succession of black to grey shales with planar to wavy lamination and good fissility. These shales are typical of the middle member in the area of study (Ferguson, 1983; Moore and Ferguson, 1986). Sandstone beds show lenticular and cross-bedding. In general, sandstone sequences fine upward.

In areas where it was possible, the middle member was distinguished using grain-size, paleosols, and fossil plants as field markers. The middle member was observed in Summerville, Mutton Cove, and in the southern portion of Bass Creek (Fig. 1.2). It appears as a succession of black shales and fine grey sandstones. Black shales show planar to wavy lamination and good fissility. Sandstone beds range from few centimetres to several metres in thickness, and display planar and cross stratification.

The upper member is a coarse siliciclastic-dominated succession that includes light grey, coarse-grained sandstone (quartz arenite), medium to fine grey sandstone, and grey to dark grey shale (Moore, 1996). Minor fine conglomerate occurs locally. Sandstone beds show planar and cross-bedding. A distinctive coarse-grained, quartzose sandstone unit, identified by Moore (1986) as 'glass sand marker bed', was recognized in the Summerville area. The upper member appears pedoturbated and mudcracked in places, and paleosol levels are abundant. The thickness of the upper member of Horton Bluff Formation is estimated to be 120 m, but according to Moore (1996) the upper member may be much thicker in the area from Cheverie to Walton.

The upper member was observed in Summerville, Bass Creek, Cambridge Cove, Little Rainy Cove, Rainy Cove, Walton, and Tennycape (Fig. 1.2, Fig. 2.1). The thickness of the coarser sandstone intervals range from 0.2 to 1 m. The sandstone beds are typically well indurated. Ripple marks and truncation of foreset surfaces were used as way-up field indicators. Paleosols weather grey-yellow, and contain mudcracks and septarian carbonate concretions. Several top surfaces display Lycopsid fossils, whereas some bottom surfaces show positive groove and load casts.

Convolute lamination in fine sandstone beds is common. Coarse quartzitic sandstone beds of the upper member were observed in Summerville, Walton, Tennycape, and Lower Selma (Fig. 1.2).

2.1.2. Cheverie Formation

The Horton Bluff Formation is conformably overlain by the Cheverie Formation. The Cheverie Formation consists of grey to red-grey shale and fine grey, variably calcareous sandstone, and locally arkosic medium-grained sandstone. Sandstone beds display planar and cross-stratification. Red to green mudrock with rootlets, mudcracks, and pedogenic features, appears interbedded occasionally (Moore, 1996). In the upper part of the Cheverie Formation, calcareous and siliceous quartz arenite and minor well-laminated dark grey micaceous shales are present. Depositional environments are interpreted here as continental, with highly seasonal to increasingly dry climate (Moore, 1996). The estimated thickness for the Cheverie Formation ranges from 100 to 260 m (Ferguson, 1983).

The Cheverie Formation was observed in Summerville, Cheverie, and Walton areas (Fig. 1.2, Fig. 2 B). In Summerville it appears as brown-red arkosic, fine to medium-grained, calcareous sandstone, locally interbedded with dark red shale. Rootlets, mud cracks, and pedogenic features were identified in Cheverie and Walton areas.

2.2. Windsor Group

The Windsor Group, of Middle to Late Visean age (Utting, 1987), consists of marine limestone, evaporite, halite, and subordinate shale. It is widely distributed throughout the study area and represents the only marine incursion into the Maritimes during the Late Paleozoic (Fig. 1.2, Fig. 1.3). The estimated total thickness of the Windsor Group reaches about 800 m in the type area of Windsor, Nova Scotia (Moore, 1996).

In the Minas Basin, seven formations have been defined and mapped in the Windsor Group (Moore and Ryan, 1976; Moore and Ferguson, 1986). These are, from base to top, the Macumber, White Quarry, Stewiacke, Miller Creek, Wentworth, Pesaquid, and Murphy Road formations (Moore and Ryan, 1976). Two of the formations, the Macumber Formation and the White Quarry Formation, were observed in the southwest, northwest, and northeast of the study area.

The Windsor Group was observed in tectonic contact with the Horton Group, although transitional conformable contacts have been reported locally (Moore, 1996). Tectonic contacts at depth between the Horton and Windsor group were documented by drill holes in Summerville, Walton Mine, and Tennycape areas (Chapter 4).

2.2.1. Macumber Formation and Pembroke Breccia

The Macumber Formation (Weeks, 1948) consists of grey-brown limestone, which is finely laminated, variably argillaceous and arenaceous, locally dolomitized and sideritized (Moore, 1996). The Macumber Formation marine carbonate deposits represent the first transgression in an arid continental basin. The estimated thickness of the Macumber Formation ranges from 1 to 20 m (Ferguson, 1983; Moore, 1996). Limestone breccia with variably siliciclastic-rich limestone matrix is locally present near the top of the Macumber Formation. Some breccias and conglomerates have been described near the base of the formation (Lavoie et al., 1995). These breccias are descriptively referred to as Pembroke Formation (Weeks, 1948) or Pembroke Breccia. Outcrops of the Macumber Formation and Pembroke Breccia were observed in the Cheverie and Walton areas (Fig. 1.2, Fig. 2 C).

The brecciation processes that were responsible for the genesis of the Pembroke Formation have been a subject of debate (Clifton, 1967; Giles and Lynch, 1994; Lavoie et al., 1995). The base of the Macumber Formation contains decimetre-thick intervals of breccia, described as oligomictic, clast-supported, containing mudstone clasts and a fine-grained carbonate matrix (Lavoie et al., 1995). Secondary dissolution porosity, with centimetre-sized pores filled with calcite and bitumen, has been observed in core from the Walton area (Lavoie et al., 1995). This basal breccia has been recently interpreted as synsedimentary (Lavoie et al., 1995).

The term Pembroke Breccia has also been employed informally in the Walton area to designate a breccia at the top of the Macumber Formation (O'Sullivan and Macfie, 1988; Hudgins, 1984). This polymictic breccia contains red to brown mud and evaporite clasts; the matrix consists of very fine limestone grains. Dissolution features are visible in the matrix and limestone clasts. Oxidation rims surround many clasts. This upper breccia of the Macumber Formation has been recently interpreted as karstic (Lavoie et al., 1995). In the present work, the term Pembroke Breccia designates the late karstic oxidized unit at the top of the Macumber Formation. This unit has been recognized in logged intervals from drill holes in the Walton and Tennycape areas (Chapter 4).

In the eastern portion of Nova Scotia, some 70 km from the study area, another type of breccia has been defined by Lavoie and Sangster (1995). The breccia is best described as oligomictic, matrix-supported, with no sedimentary or dissolution structures visible. Clasts consist of shaly limestone and the matrix is very fine, mostly limestone and barite. Stylolites are abundant and jigsaw puzzle textures are common. About 1500 m of overlying Windsor strata are abruptly disrupted in Aulds Cove (eastern Nova Scotia), where the Cumberland Group overlies this breccia. These observations led Lavoie and Sangster (1995) to interpret the unit at Aulds Cove as a tectonic breccia.

2.2.2. White Quarry Formation

The White Quarry Formation (Moore and Ferguson, 1986) consists of thick stratified massive anhydrite and gypsum with thin interbeds of limestone, dolostone, and rare halite. These deposits represent an evaporite basin centre dominated by anhydrite with minor halite and siliciclastic carbonate (Moore, 1996). The thickness of the unit is known to range from 100 to 300 m.

The White Quarry Formation is the most recognizable and widely distributed unit in the Summerville area (Fig. 1.2, Fig. 2 D) where it appears as a succession of stratified to massive, white to pink anhydrite and gypsum, with thin interbeds of structureless grey limestone. It has been inferred inland, where a few outcrops occur (for example, in the Walton area). The White Quarry Formation is also exposed in the east portion of the study area, in the Old Quarry zone (Fig. 1.2).

2.2.3. Middle and Upper Windsor Formations

The Stewiacke Formation conformably overlies the White Quarry Formation, although its distribution in the study area is not well established (Moore and Ferguson, 1986). It consists of thick stratified salt with rare anhydrite layers (Fig. 1.3). The thickness of the unit in the study area is known to locally exceed 50 m (McDonald, 2001).

The Miller Creek and Wentworth Station formations are interstratified successions of gypsum and anhydrite, subordinate thin salt and fine sandstone layers (Fig. 1.3). The Pesaquid Lake Formation represents continental red beds, marine evaporite and limestone. The Murphy Road Formation contains red fine sandstone, fossiliferous marine carbonate, minor gypsum and anhydrite (Moore and Ferguson, 1986).

In the study area, Moore (1996) stated, "the existence of the Miller Creek and Wentworth formations within the map areas is somewhat conjectural". In the Stanley subarea (Fig. 1.2) Boehner and Edgecombe (1993) and Boehner (1994) remark on the uncertain identification of these formations. McDonald (2001) attributed the unexpected thickness of the Windsor Group near Cheverie to grey calcareous shales, minor limestone, and salt layers that may correspond to the Stewiacke and the Miller Creek formations, never documented in previous oil wells. These observations indicate that these formations have an unknown distribution and may contain abrupt changes in thickness.

2.3 Mabou Group

The Mabou Group (Late Visean to Early Namurian) represents the evaporitic marine to variably saline continental lacustrine deposition characteristic of the Windsor group (Moore, 1996; Moore et al., 2000). In the left bank of the Kennetcook River, south of the area of study, Moore et al. (2000) identified the

Mabou Group as a grey and minor red succession of mudrock and evaporite. Mudrock comprises calcareous and laminated shale, siltstone, and fine sandstone (Fig. 1.3). Interbeds of gypsum, anhydrite, and rarely salt, occur near the base. South of the area of study, the thickness of the Mabou Group ranges from 130 m to more than 250 m.

2.4. Cumberland Group

The Cumberland Group includes the Scotch Village Formation, of Namurian to Middle Westphalian age (Fig.1.3). The Scotch Village Formation consists of grey to minor yellow-red sandstone and grey-brown shale, rare thin coal and plant debris. Sandstone beds are cross-bedded, generally fine upward, and occasionally are calcareous. Sandstone and shale are altered by pyrite and chalcopyrite (Boehner and Edgecombe, 1993). This unit represents continental fluvial floodplain of braided systems (Moore, 1996). The thickness exceeds 300 m in the Scotch Village type area. The contact between the Cumberland and the Windsor groups is unconformable (Moore, 1996).

Outcrops of the Scotch Village Formation were observed in the banks of the Kennetcook River (Fig. 1.2) as yellowish grey, fine-grained sandstone, cross-bedded, and moderately weathered. Beds appear indurated, are about half a meter thick, contain plant debris, and seem undeformed. These characteristics have been

observed in drill hole STY93-1 (Fig. 1.2), drilled by the Nova Scotia Department of Natural Resources (Boehner and Edgecombe, 1993).

2.5. Fundy Group

The Fundy Group (Klein, 1962) includes in its base the Wolfville Formation, which is Middle to Late Triassic in age (Fig. 1.3). The Wolfville Formation consists of coarse to medium pink-brown sandstone and conglomerate. Minor mudsone occurs. Cross-bedding in sets of several meters is common. Dominant sandstone compositions are arkose, lithic arkose, and feldspathic litharenite. These rocks are typical deposits of braided systems and alluvial fans (Moore, 1996; Moore et al., 2000). The thickness of the formation has been estimated to be about 363 m in the type area of Wolfville (Klein, 1962). The Wolfville Formation crops out on the south shore of the Minas Basin, unconformably overlying the Horton Group (Fig. 1.2).

2.6. Palynology

Palynological analyses of rocks mapped as Horton Bluff Formation in the coast and some inland areas were carried out after a suggestion of McDonald (2001) that these units could be younger. Black to dark grey shale and minor fine sandstone were channel-sampled, cross-cutting strata in order to obtain representative specimens. Details and identifications are given in Appendix I, Palynology Reports.

The type-section of the Horton Bluff Formation in Blue Beach, Horton Bluff, was sampled to control further palynological analyses, and yieded in a Late Tournaisian age (Utting, 2002a, included here as Appendix I). Palynomorphs were identifiable in samples obtained at the east portion of the Tennycape area and central Rainy Cove, all assigned to the Upper Tournaisian. These ages are consistent with Horton Group rocks.

The upper section of well Cheverie-01 was sampled in six intervals (805-810 m, 575-580 m, 285-290 m, 110-115 m, 45.0-45.5 m, and 30-35 m). Sufficient taxa were identifiable to provide a Late Tournaisian age in all samples (Utting, 2002b, included here as Appendix I). On the basis of their palynomorphs, these samples were identified as Cheverie Formation and the upper member of the Horton Bluff Formation (see Appendix I).

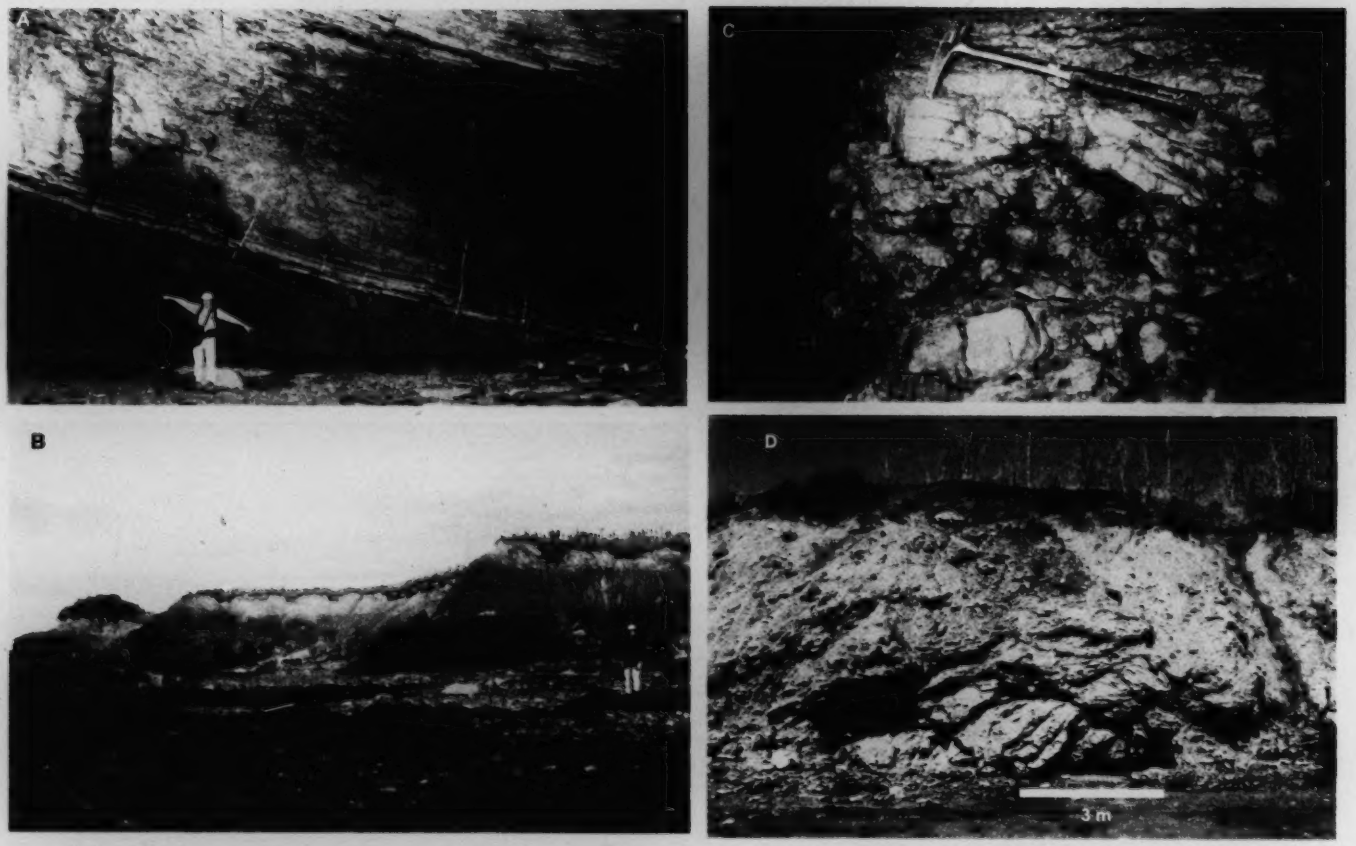


Figure 2.1: Typical aspect of the main units in the study area. A) Horton Bluff Formation (person for scale); B) Cheverie Formation (person for scale); C) Pembroke Breccia (hammer for scale); D)White Quarry Formation.

3. Field data

The coastal portion of the area of study was divided into nine mapping areas: Summerville, Cheverie, Mutton Cove, Bass Creek, Cambridge Cove, Little Rainy Cove, Rainy Cove, Walton, and Eastern (Fig. 1.2). The Cheverie area has been mapped by Johnston (1999) and his findings were presented in Chapter 1. Most of the areas were mapped at 1:5000, although more detailed scales were used in some cases (Mutton Cove, Little Rainy Cove). Less detailed scales were employed in the Summerville and Eastern zones, since outcrops are discontinuous and limited to a few sectors.

The mapping areas can be reached by Highway 215 (Fig. 1.2). Secondary roads provide good access to the shore and some inland zones. In most areas, the quality of exposures is good in the cliffs and the immediate shore. Offshore outcrops, though exposed at low tide, are more difficult to work and hazardous due to the tides, thunderstorms, mud platforms, seaweed, and encrusting organisms.

The deformation of the Horton Group was studied in detail from Summerville to Walton. The Horton Bluff Formation is present in all mapping areas as a clastic succession of grey to black shales and sandstones, which are planar to cross-stratified. The Cheverie Formation was observed in discontinuous outcrops at Cheverie and Walton (Fig. 1.2) as brown-red to green-grey, fine to medium-grained, arkosic sandstone, that is locally interbedded with dark red shales.

The Macumber Formation (Windsor Group) crops out in Cheverie and Walton (Fig. 1.2) as a light brown succession of fine-grained limestone. The

Pembroke Breccia was observed closely associated with the limestone as a red-yellow, clast-supported, polymictic breccia. Clasts are red to brown, consisting of mud and evaporite. The White Quarry Formation of the Windsor Group consists of white to pink anhydrite and gypsum, which are stratified to massive.

The Wolfville Formation (Fundy Group) crops out in the coast and offshore areas. It consists of grey-pink coarse sandstones, cross-stratified, and interbedded fine conglomerates. The Wolfville Formation appears undeformed in most areas, although a number of faults were recorded in Little Rainy Cove (see below). In most areas, an angular unconformity between the Wolfville and the Horton Bluff Formation was observed near the coast and offshore (Fig. 1.2).

3.1. Summerville area

The Summerville mapped area has been delimited by a rectangle defined by the Kennetcook River, the East coast of the Avon River, Indian Point, and a one km-wide inland covered section at the east (Fig. 3.1).

Strongly deformed outcrops of the Horton Bluff Formation were mapped in the central and south portions of the Summerville area. The White Quarry Formation is the most recognizable unit in the centre and south portions of the map, inferred to be in tectonic contact with Horton Bluff rocks. Cheverie and Scotch Village outcrops were observed in the north and the south portions of the map, respectively.

The upper member of the Horton Bluff Formation (Fig. 3.2A) contains a distinctive quartzose sandstone subunit which has been employed for recognition and mapping of the upper member by Moore (1986). This subunit consists of grey, coarse-grained, cross-bedded quartzose sandstone that fines upward to medium grain. The contact between the Horton Bluff Formation and the Cheverie Formation is generally conformable, except in areas where faults have been inferred (zones B and C in Fig. 3.1).

The White Quarry Formation gypsum and anhydrite were observed as fine opaque masses, idiomorphic aggregates within cavities, and fibres filling fractures (Fig. 3.2B). The contact between the Horton Bluff Formation and the White Quarry Formation seems tectonic (see Section 3.1.1.2).

The Scotch Village Formation of the Cumberland Group is poorly exposed in the margins of the Kennetcook River (Fig. 3.1) as yellow to reddish grey, medium to

fine grained, cross bedded sandstones. Indurated half-meter thick beds with plant debris are common. The observed outcrops appear as subhorizontal undeformed successions.

3.1.1. Structure

Outcrops in the Summerville area are discontinuous, limited to the cliffs and portions of the beach. Most of the inland contacts in the map (Fig. 3.1) are inferred. The deformation is restricted to Horton and Windsor groups. The Scotch Village Formation appears as a subhorizontal, relatively undeformed sequence in the banks of the Kennetcook River.

Folds range transitionally from open in the north area of the map to tight in the south. Most of the faults were observed in the coast; their inland projection was inferred. Fabrics, when present, are not strong and are mostly restricted to the Horton Bluff Formation and some sectors of the White Quarry Formation.

3.1.1.1. Folds

The map of Summerville has been divided into four main zones (A, B, C, and D in Fig. 3.1) with structural differences. Folds are evident in all outcrops of the Horton Bluff Formation and the Cheverie Formation. Layering of the White Quarry

Formation is discontinuous and displays variable thickness, which makes individual folds difficult to identify.

In zone A (Fig. 3.1), outcrops of the Cheverie Formation display open folds, which plunge gently to the south and northwest, and are mostly symmetric. Fold wavelengths are about 3 metres. Axial planes strike northeast-southwest, north-south, and northwest-southeast, and are mostly subvertical. Bedding surfaces appear clustered near the centre of the stereonet (Fig. 3.3).

In zone B of the map (Fig. 3.1, Fig. 3.3), folds affect the Upper Member of the Horton Bluff Formation and the Cheverie Formation. Folds are open, gently inclined to recumbent, and plunge gently to the southeast. Fold wavelengths range from 10 to 20 m. Disharmonic folds were observed at the metre-scale.

In zone C, the sedimentary layering of White Quarry gypsum defines a 40 m half-wavelength antiform that plunges steeply to the northwest (Fig. 3.2C). The cliff profile for zone C (Fig. 3.4) shows that part of the Horton Bluff Formation is affected by folding. Folds are open to tight, plunge gently to the north, and wavelengths range from 2 to 0.5 m. Axial surfaces are upright to steeply inclined, and strike north-south. These folds can be classed as similar folds (Davis and Reynolds, 1996). Folds become tighter in the proximity with the gypsum of the White Quarry Formation.

In zone D of the map (Fig. 3.1), the Middle Member of the Horton Bluff Formation crops out in contact with the White Quarry Formation, displaying a complex fold pattern. Folds are open to tight; most plunge to the southeast and the northwest (Fig. 3.3). They become tighter and disharmonic in the proximity of the

contact between the Horton and the Windsor groups. Fold wavelengths range from 2 to 10 m. In the coast of the Kennetcook River and surrounding areas, the Scotch Village Formation appears as a homoclinal succession that strikes northeast-southwest and dips gently to the northwest (Fig. 3.1).

3.1.1.2. Faults

In zone A, the Cheverie Formation appears gently folded, whereas in zone B Horton Bluff and Cheverie strata are strongly deformed. Between zones A and B, a fault (of unknown orientation) has been inferred because of abrupt changes in bedding orientation, deformation, and the repetition of Cheverie strata. In zone B, the upper member of the Horton Bluff Formation is in conformable contact with the Cheverie Formation.

In zone C, White Quarry evaporites are in contact with Horton Bluff sandstones. This contact must be tectonic, since the Cheverie Formation is missing. In this part of the map, the White Quarry Formation is inferred to be overlain by the Horton Bluff Formation with a tectonic contact (Fig. 3.4, Fig. 3.5).

In zone C, the White Quarry Formation displays matrix supported breccia zones that are approximately 1 m thick (Fig. 3.6 A-B). The clasts are angular, equidimensional, from 2 to 5 cm, and constitute 30% of some outcrops. The clasts consist of laminated shales, anhydrite, and gypsum. Aphanitic to fine aggregates of gypsum form the matrix of the breccia. Tension gashes were observed in the White

Quarry Formation, striking northwest-southeast and in some cases displaying *en echelon* arrangements. Tension gashes are subhorizontal and are filled with gypsum fibres (Fig. 3.4, Fig. 3.6 B-C), which plunge steeply towards the north and the south.

In zone D, subvertical to irregularly oriented surfaces of contact between the White Quarry and the Horton Bluff formations were observed and inferred in a number of locations (Fig. 3.1). The repetition and orientation of these contacts, cross-cutting the strike of bedding, suggest a tectonic relationship.

3.1.1.3. Fabrics

Discontinuous and weak cleavage was observed in zone C, visible as domains of darker clay minerals in shales and fine sandstones of the Horton Bluff Formation. Shales of the Horton Bluff Formation show shear band foliations (Davis and Reynolds, 1996) (Fig. 3.4, Fig. 3.2D). Although the degree of ductility and deformation of the shales is different from those found in mylonites, the kinematic significance is inferred to be similar. Both shear bands and the fabric they cut strike northeast-southwest and dip steeply to the northwest (Fig. 3.5). These orientations suggest a northwest-southeast direction of transport of the Horton Group (Fig. 3.5A-B).

3.1.2. Discussion

The stratigraphic relationship between Horton and Windsor groups appears inverted in zone C of the map. In an undisturbed sedimentary sequence, the evaporites would be expected to be found on top of the Horton Group. This inversion and the asymmetric fabrics indicate a southward transport of Horton strata on top of Windsor evaporites (Fig. 3.5A-B). Zones B and C show strongly deformed Horton Bluff and Cheverie strata, possibly thrusted over Windsor evaporites. Allochthonous Horton rocks have been interpreted in the Cheverie area to the north by Johnston (1999).

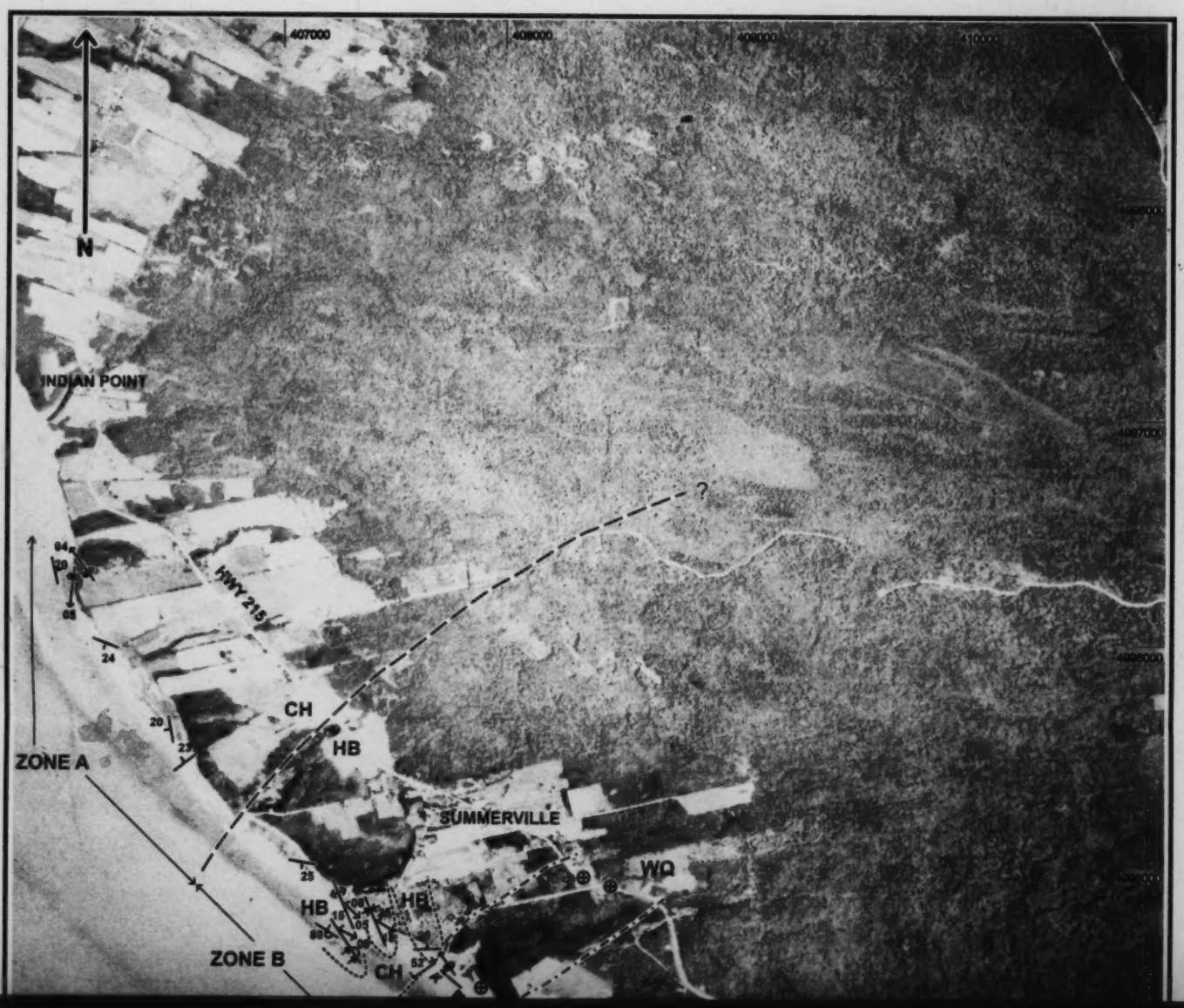
In zone C, the above-described evaporite antiform (Fig. 3.4) displays tension gashes and gypsum fibres that indicate subvertical extension within evaporites. The large-scale antiform is here interpreted as an evaporite diapir. If this interpretation is correct, the subvertical contacts inferred between the Horton and the Windsor Groups in zones C and D correspond to several diapires.

Breccia zones associated with fractures were documented within the inferred evaporite dome (Fig. 3.4). Johnston (1999) observed similar breccias near the contact between Horton and Windsor rocks in Johnson Cove (Section 1.2). These breccias probably resulted from emplacement of Windsor evaporite diapirs that disrupted Horton strata.

In zone D, folds affecting the Horton Bluff Formation become tighter and more disharmonic in the proximity of Horton-Windsor contacts. It is possible that after the thrusting of Horton on top of Windsor Group, the rise of evaporite domes

locally deformed the overlying Horton strata, producing variably oriented folds near the diapir flanks.

Zones of localized deformation of adjacent sedimentary rocks (brecciation, fracturing, folding) as a result of growth of salt diapirs have been designated "drag zones" (Jackson and Talbot, 1994; Davison et al., 1995). Drag zones are proposed here to explain the variable pattern of folding and the presence of breccias in the Summerville area. In Nova Scotia, drag zones of larger scale related to the Windsor Group were studied in western Cape Breton by Alsop et al. (2000).


407000
408000
409000
410000
N
INDIAN POINT
HWY 215
?
ZONE A
ZONE B
CH
HB
SUMMERVILLE
WQ
HB
HB
CH

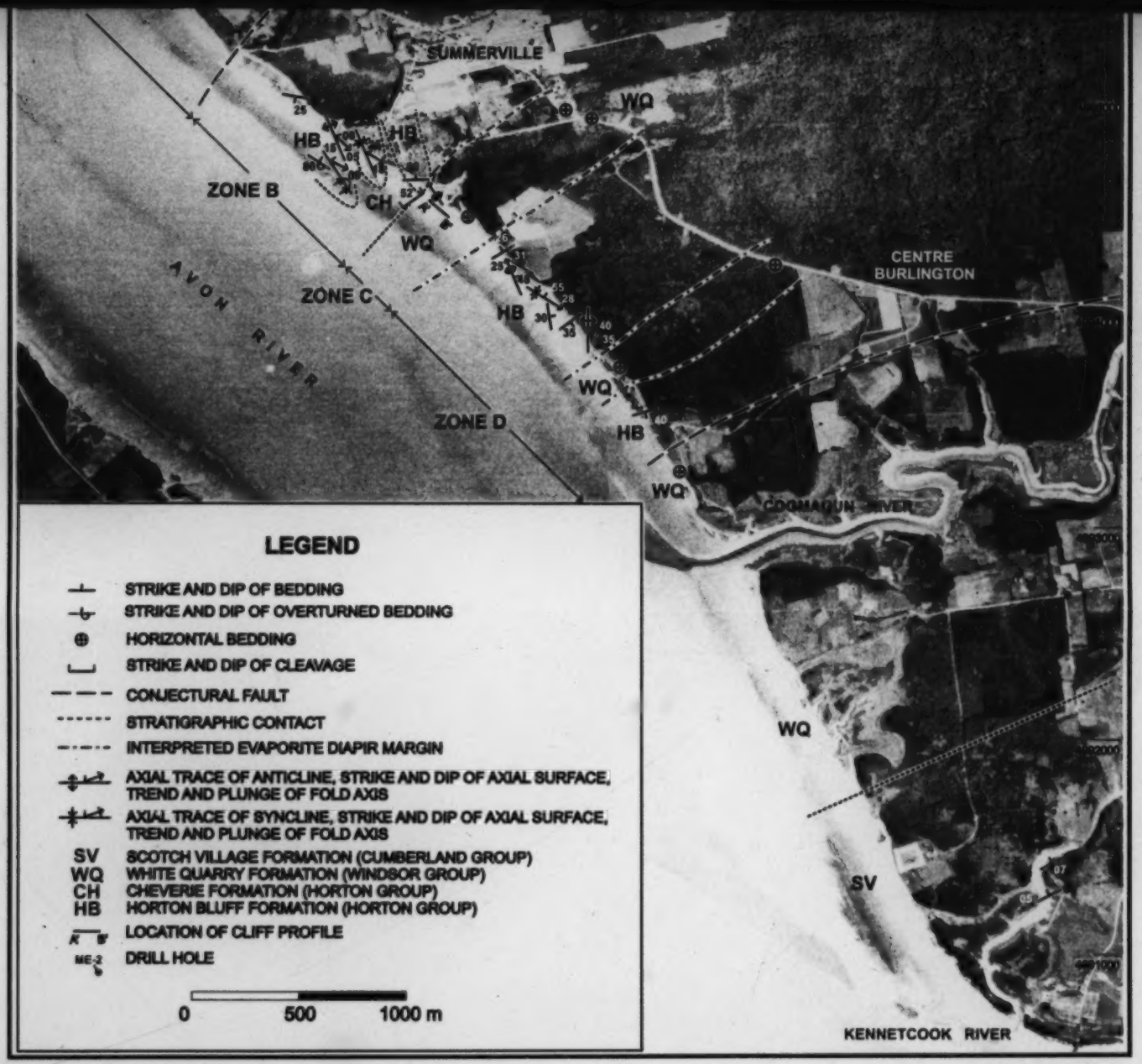


Figure 3.1: Map of the Summerville area.

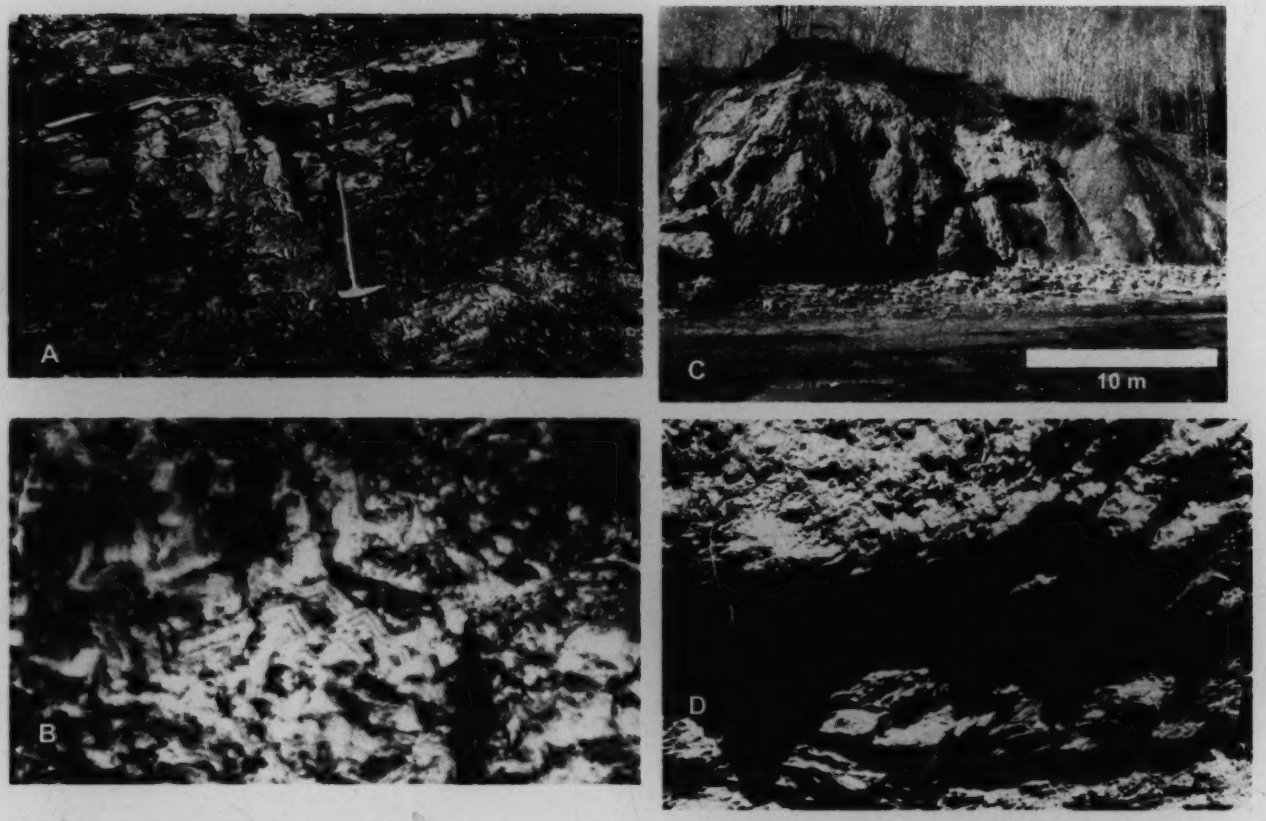


Figure 3.2: Horton Bluff and White Quarry Formations in the Summerville area. A) Horton Bluff sandstone and shale (hammer for scale). B) White Quarry gypsum, idiomorphic crystal aggregates and chemical layering textures (pen for scale). C) White Quarry evaporites in zone C, gypsum antiform (bar for scale). D) Horton Bluff shale showing fabrics analogous to S-C fabrics (pen for scale).

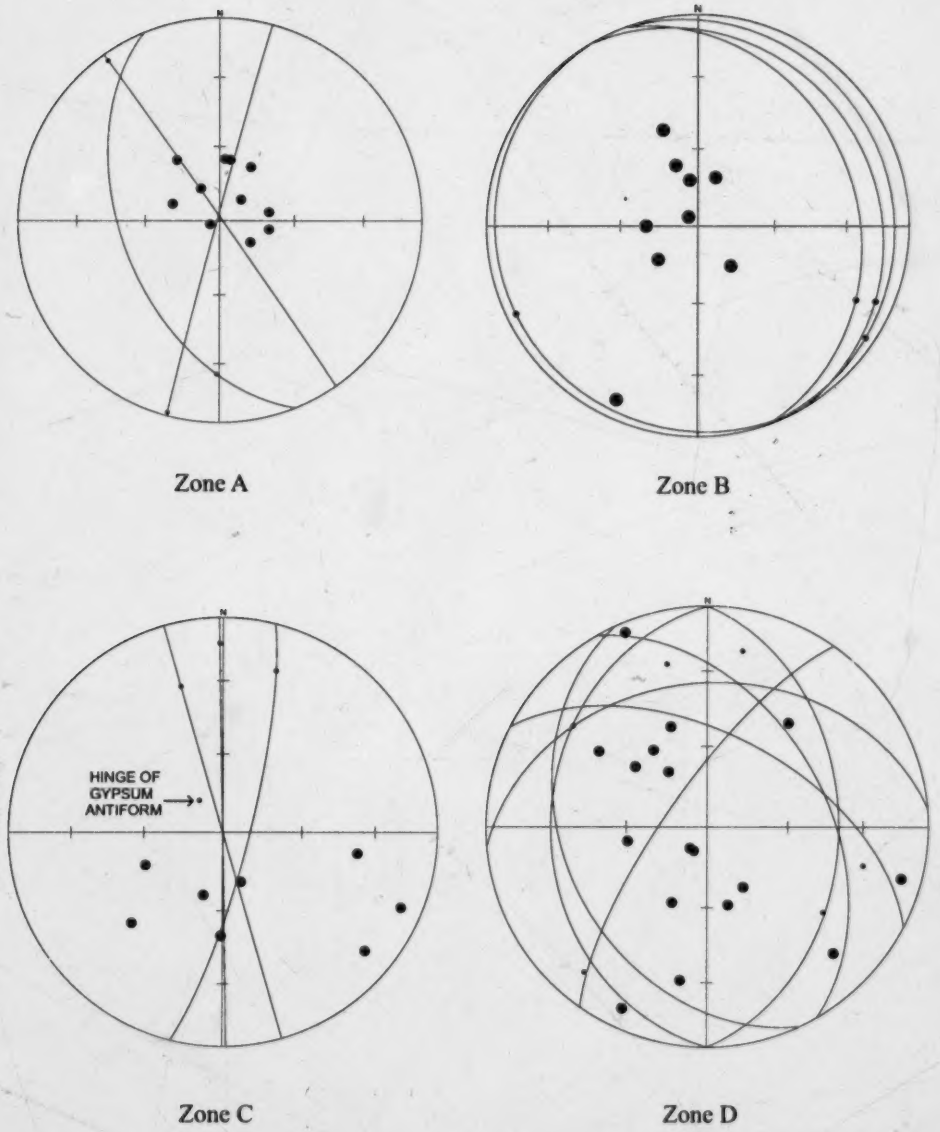
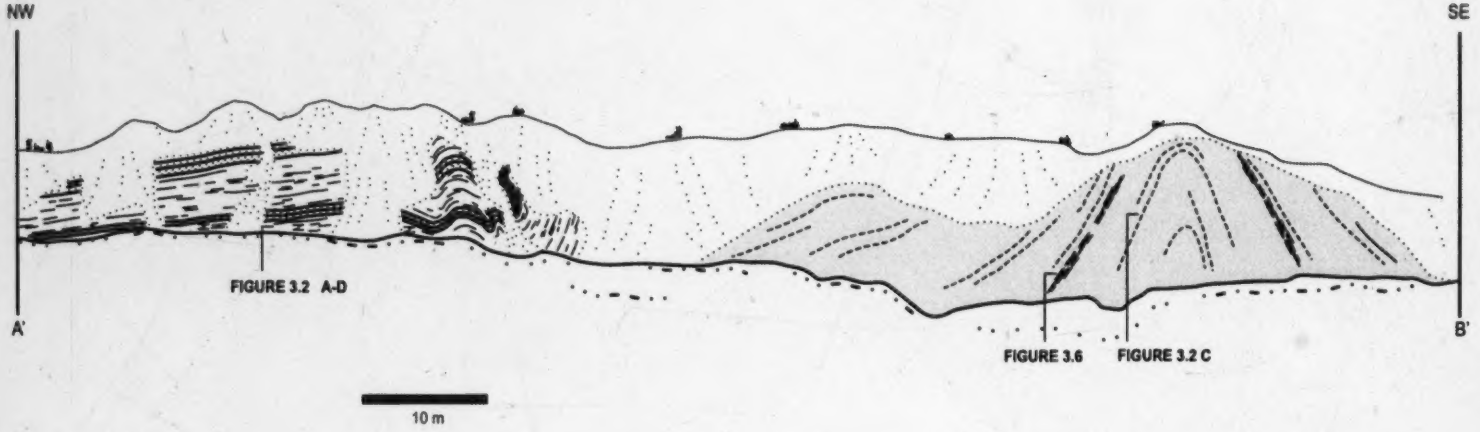


Figure 3.3: Steregraphic projections, zones A to C, Summerville area.
Fold axial planes (great circles), poles to bedding (larger dots), and fold hinges (smaller dots).

Figure 3.4: Field sketch of outcrop at location A'B' (Fig. 3.1) showing deformed Horton Bluff Formation clastics in contact with White Quarry Formation evaporites.



SANDSTONE BEDS, HORTON BLUFF FORMATION (HORTON GROUP)
SHALE, HORTON BLUFF FORMATION (HORTON GROUP)
GYPSUM, WHITE QUARRY FORMATION (WINDSOR GROUP)
BRECCIA ZONE
LOCATION OF INTERPRETED SHEAR FABRICS IN SHALE
COLLUVIUM

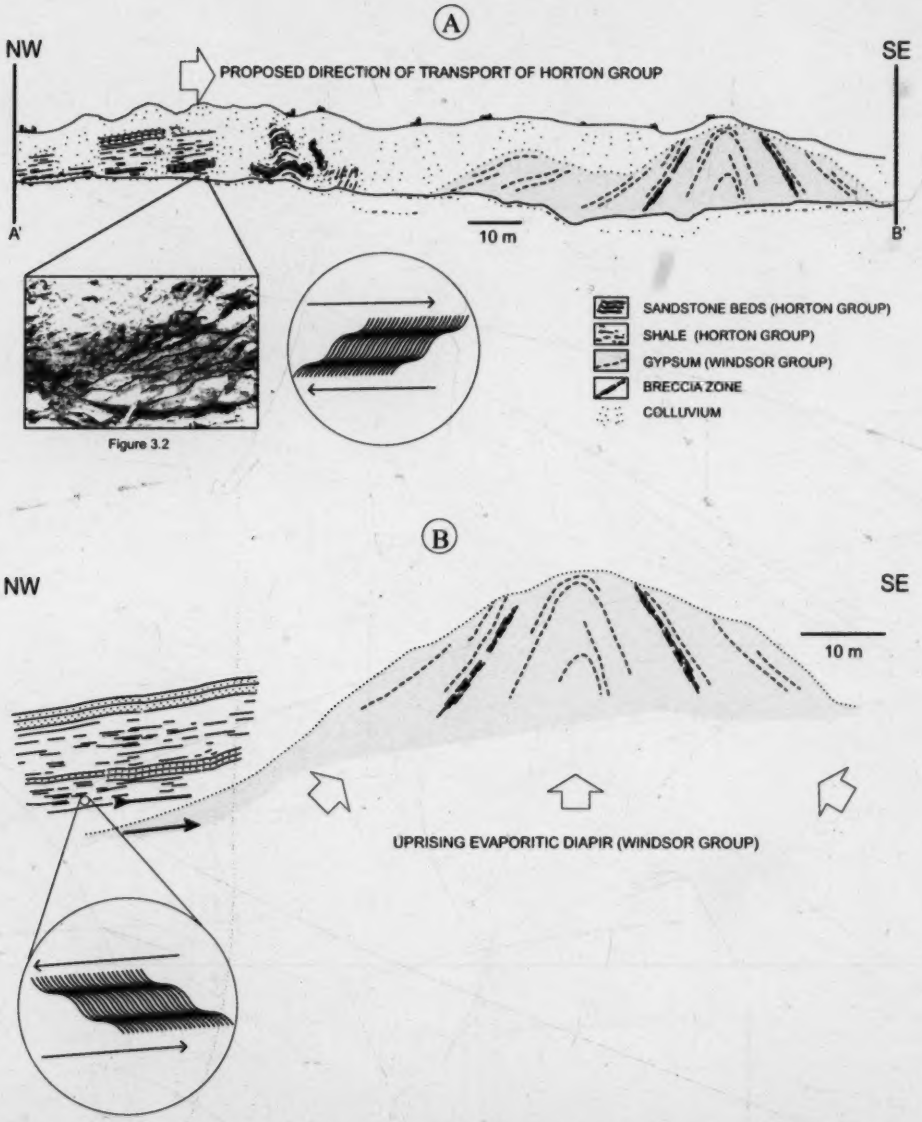


Figure 3.5: Cliff profile A'B' in zone C, Summerville. A) Interpreted shear fabrics (photo, pen for scale) affecting Horton shales northwest of the interpreted evaporite diapir (Fig. 3.4). Fabrics indicate southward direction of transport, possibly due to overthrusting of Horton strata, which appear strongly deformed on top of Windsor evaporites. B) Diagram showing relationship of interpreted shear fabrics in Horton shale to adjacent diapir. If the shear fabrics were entirely due to diapirism, northward direction of transport would be observed. This is not the case.

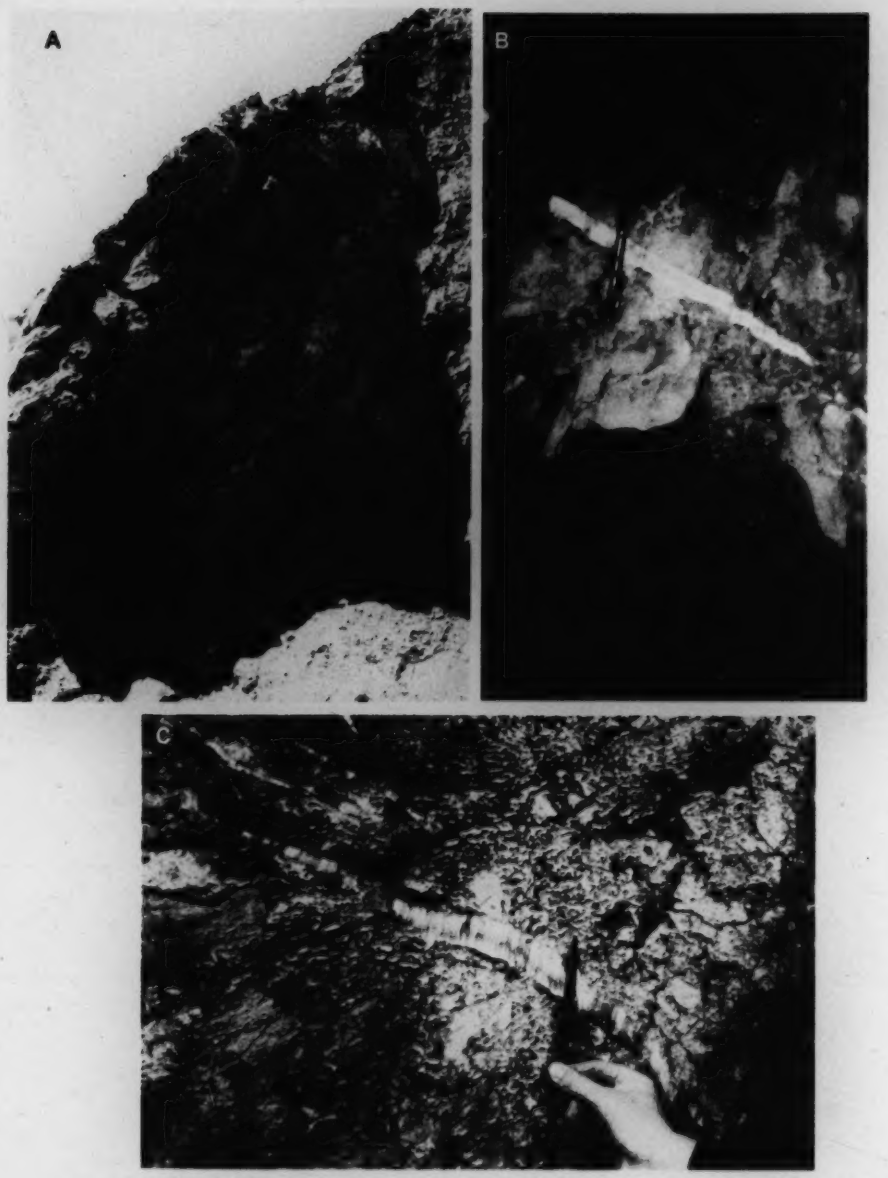


Figure 3.6: Breccia zones in the White Quarry Formation, Summerville area. A) Breccia in White Quarry Formation, Zone C (hammer for scale). B) Close-up of breccia and tension gashes (pen for scale). C) Subvertical gypsum fibres (pen for scale).

3.2. Mutton Cove area

The Mutton Cove area includes the coastline from Mutton Cove to Bass Creek (Fig. 3.7) extending 1 km inland. The middle member of the Horton Bluff Formation is the only unit that crops out in this area.

3.2.1. Structure

The map can be divided into two zones for structural studies (Fig. 3.7). Zone A, the southwest sector of the map, offers a north-south section of the structures. Zone A is characterized by zones of faulting, shown in detail in Fig. 3.8. Zone B, the central and northeast portion of the map, offers an east-west section of the structures. In general, folds can be observed in the beach and the cliffs, and fabrics are locally developed. Measured bedding surfaces are clustered near the centre of the net, with predominant dips gently to the west (Fig. 3.9 A).

3.2.1.1. Folds

Zones A and B show open symmetric folds, with 8 -20 m wavelengths. Most folds plunge gently to the southwest and northeast, although a few plunge west-northwest and south-southeast (Fig. 3.7, Fig. 3.9 B). Axial surfaces strike northeast-southwest and incline steeply to the northwest and southeast (Fig. 3.9 B).

In zone A, small-scale folds and fractures are observed in a zone of faulting (Fig. 3.8). These folds are open to tight, with wavelengths between 1.5 and 2 m, and

plunge gently to the northeast and southwest. Axial surfaces are upright and strike northeast-southwest.

At a smaller scale in the cliffs, some beds are discontinuous, and disharmonic open folds with wavelengths of about 2 meters are observed. Measurement of these small-scale folds was difficult because they are well exposed only in inaccessible higher parts of the cliffs.

3.2.1.2. Faults

In zone A, south of the zone of faulting mapped in Fig. 3.8, a number of closely-spaced faults strike east-west and dip gently to the north (Fig. 3.9 D, shown as a reverse fault zone in Fig. 3.7). Typical offsets of bedding are about three meters and show reverse displacements.

In zone A, faults are more abundant than in the rest of the map. Straight fault traces can be followed from the cliff to the beach (Fig. 3.7). Fig. 3.8 shows a pattern of anastomosing faults, joints and veins. Fault 1, in the south portion of the map, is subvertical and strikes northwest-southeast. In the fault plane, subhorizontal slickenlines, defined by fibres and grooves, trend parallel to the strike of the fault and indicate dextral sense of displacement. Curved fault surfaces branch from Fault 1 at small angles. Areas bounded by anastomosing fault surfaces display small-scale folds (described in Section 3.2.1.1) and veins (Fig. 3.10 A, Fig. 3.8). Veins are 0.5 to 2 cm wide, strike northwest-southeast, and appear regularly spaced. Near the cliff, Fault 1 is intersected by a set of closely spaced fractures oriented almost north-south.

North and south of Fault 1, subparallel joints were observed (Fig. 3.8). Fault 2 has a general east-west strike but shows changes in orientation on a scale of metres (Fig. 3.8). The dip of the fault plane varies a few degrees although it remains mostly subvertical. Scarce subhorizontal slickenlines defined by grooves appear in the fault plane. Fault 3 is subvertical, strikes east-west, and displays subhorizontal slickenlines. The traces of Fault 2 and Fault 3 diverge to the west and northwest in plane view (Fig. 3.7, Fig. 3.8). The traces diverge also in the cliff (Fig. 3.10 C). Dips vary between 75 and 85 degrees. Offset of beds observed in the cliff is no larger than 50 centimetres. Small-scale folds described in Section 3.2.1.1 occur in the area between the traces of Faults 2 and 3 (Fig. 3.8).

A group of fractures that strike northwest-southeast and dip steeply to the northeast were observed several metres north of Fault 2 and 3 (Fig. 3.8, upper right). The fill of the fractures is white quartz. Some of these structures are associated with *en echelon* fractures, which strike east-west and are subvertical. A number of veins filled with quartz and calcite were observed in outcrops between Fault 2 and 3. These veins are up to 1 cm thick, strike northwest-southeast, and are subvertical.

In zone B, most faults are reverse and strike northwest-southeast and dip variably to the northeast and southwest (Fig. 3.7, Fig. 3.9 D). All measured normal faults strike northwest-southeast and dip moderately to the northeast and southwest (Fig. 3.9 D). A minority of reverse faults strike northeast-southwest and dip gently to steeply to the southeast and northwest. In general, the observed displacements range from 0.5 to 5 metres. Slickenlines defined by grooves were measured in many fault planes.

Most of the joints observed in areas A and B strike northwest-southeast and are subvertical or dip steeply to the northeast and the southwest (Fig. 3.7, Fig. 3.8). Joints are more frequent in Zone A and in the west portion of Zone B.

The major faults in Zone A and B combine strike-slip and reverse displacements. The fault zone mapped in detail reveals dextral and reverse displacements as well. Most folds plunge to the southwest and northeast, suggesting northwest-southeast direction of shortening. The relationship of structures suggesting shortening and strike-slip is analyzed in Section 3.2.2.

3.2.1.3. Fabrics

In this area, cleavage is weakly developed and can be observed in fine sandstones and shales of the Horton Bluff Formation. The cleavage strikes northeast-southwest and dips steeply to the northwest, axial planar to the main folds (Fig. 3.9 C). Macroscopically, the cleavage appears penetrative. Microscopic analysis reveals a discontinuous fabric defined by oriented phyllosilicates and clay minerals in domains.

Locally, near Faults 2 and 3 (Fig. 3.8) a number of cleavage surfaces strike more to the south-southwest, being non-axial-planar and appearing to transect the small-scale folds in a counter-clockwise sense (Fig. 3.10 B).

3.2.2. Discussion

In Zone A, faults display dextral strike-slip and reverse displacements. Faults 2 and 3 and the zone in between, are interpreted here as a flower structure (Harding, 1973). Traces of Faults 2 and 3 in the cliff agree with the morphology of a flower structure (Fig. 3.10 C). The flower structure can be classed as a positive flower structure or palm tree structure (Sylvester, 1984). Folds and veins mapped in the transpression zone of the interpreted flower structure have orientations consistent with dextral transpression (Fig. 3.8, Fig. 3.11). Locally, a number of cleavage surfaces near the flower structure transect the small-scale folds, possibly as a result of a dextral rotation superimposed on the initial stages of deformation.

The zone of faulting in Zone A contains fractures associated with *en echelon* arrangements that indicate a sinistral sense of shear (Fig. 3.8, upper right). These could be explained as an antithetic relation with respect to the proposed flower structure. Fault 1 is a dextral fault (based on observed slickenlines) that displays restraining bends where dextral displacement is evidenced by the orientation of small-scale folds and veins (Fig. 3.10B, Fig. 3.11). Since Fault 1 is cross-cut by Faults 2 and 3, it is considered to have occurred prior to the flower structure. (Fig. 3.8).

In Zone B, the orientation of folds is consistent with a general northwest-southeast shortening. Cleavage surfaces are axial planar to the recorded folds. The orientation of normal faults indicates a northeast-southwest extension.

Reverse faults in Mutton Cove vary greatly in orientation and could be divided into two groups. The first group is characterized by northeast-southwest

strike, mapped in Zone A and the east portion of Zone B (Fig. 3.7). The second group consist of faults that occur in the west portion of Zone B and strike northwest-southeast (Fig. 3.7). The first group is consistent with a northwest-southeast shortening, also suggested by the orientation of the main folds and cleavage surfaces. The second group, although more local, cannot be explained by the same direction of strain.

Regionally, the Mutton Cove area displays structures that indicate an extension axis of finite strain trending northeast-southwest. Structures reflecting both shortening and strike-slip suggest that dextral transpression occurred in this area. If the interpretation of a transpression zone is correct, the observed spreading of fold hinges (Fig. 3.9 B) could be the result of rotation during progressive deformation stages (Fig. 3.11). The distribution of fold hinges could also mean that the strain was heterogeneous in the area, or that fold hinges were spread after refolding by another generation of folds that occur at larger scale.

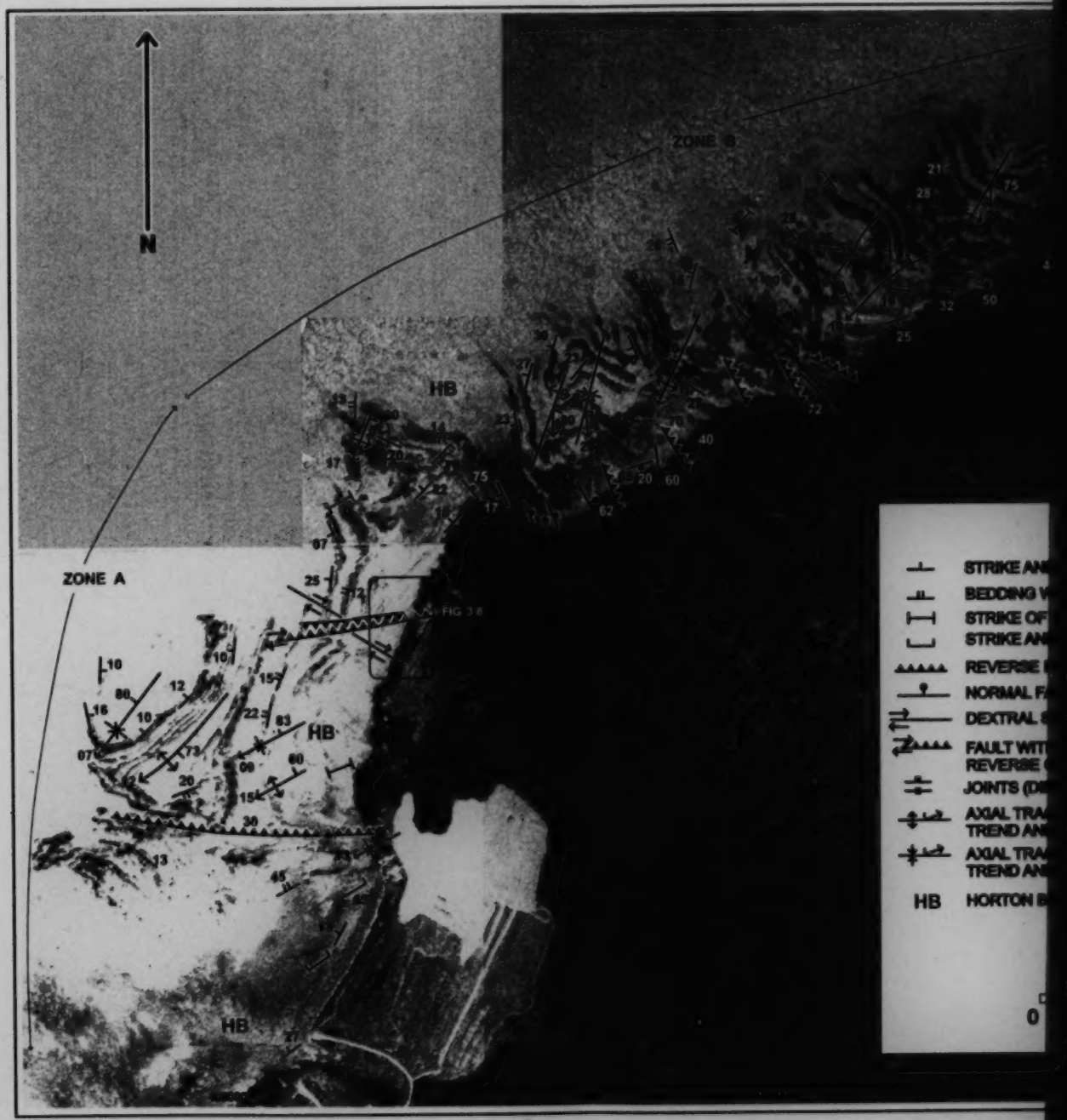
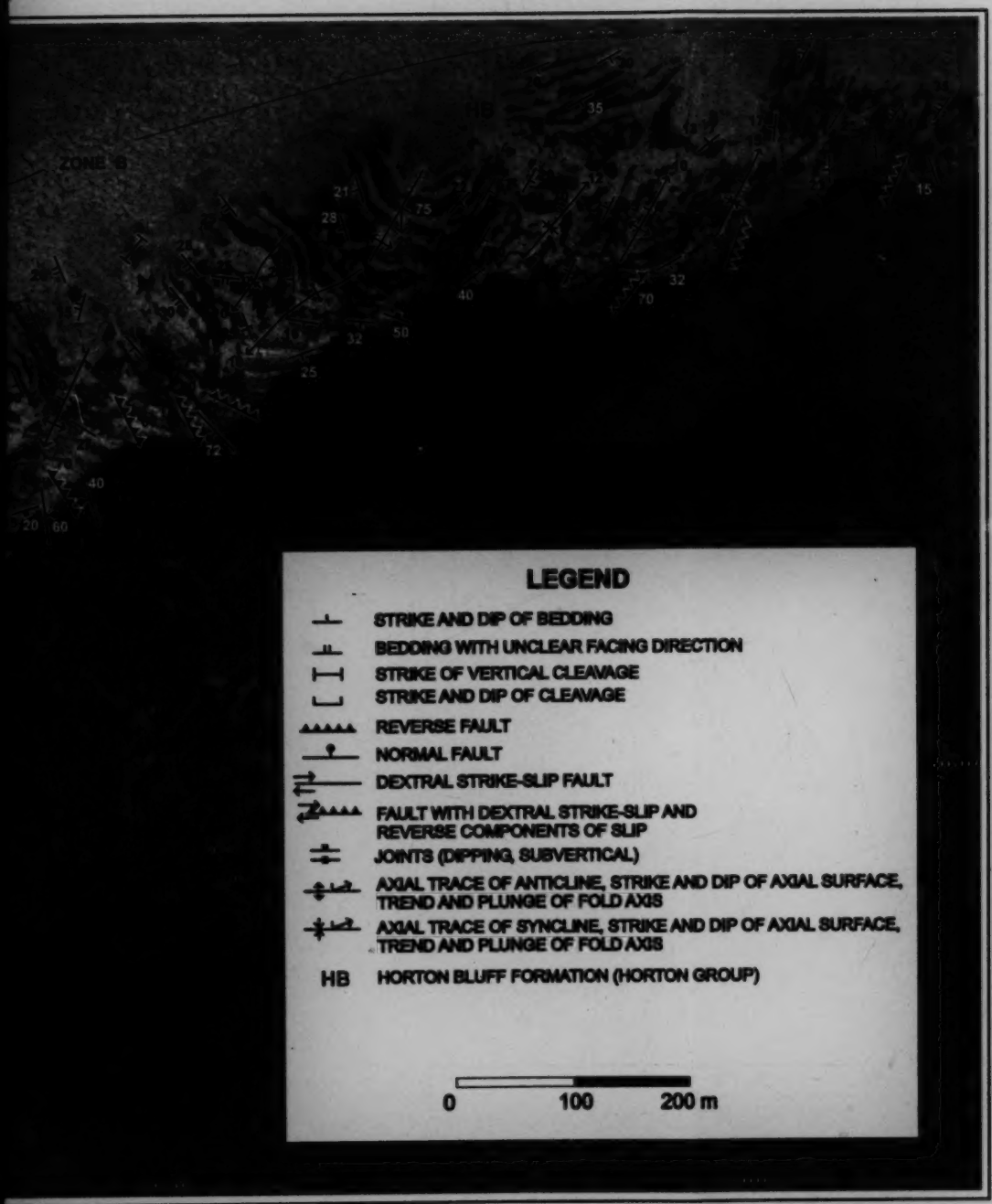


Figure 3.7: Map of the Mutton Cove area.


ZONE B
HB
35
21
28
75
15
40
70
32
32
50
25
72
40
20
60
LEGEND
STRIKE AND DIP OF BEDDING
BEDDING WITH UNCLEAR FACING DIRECTION
STRIKE OF VERTICAL CLEAVAGE
STRIKE AND DIP OF CLEAVAGE
REVERSE FAULT
NORMAL FAULT
DEXTRAL STRIKE-SLIP FAULT
FAULT WITH DEXTRAL STRIKE-SLIP AND REVERSE COMPONENTS OF SLIP
JOINTS (DIPPING, SUBVERTICAL)
AXIAL TRACE OF ANTICLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNCLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
HB HORTON BLUFF FORMATION (HORTON GROUP)
0 100 200 m

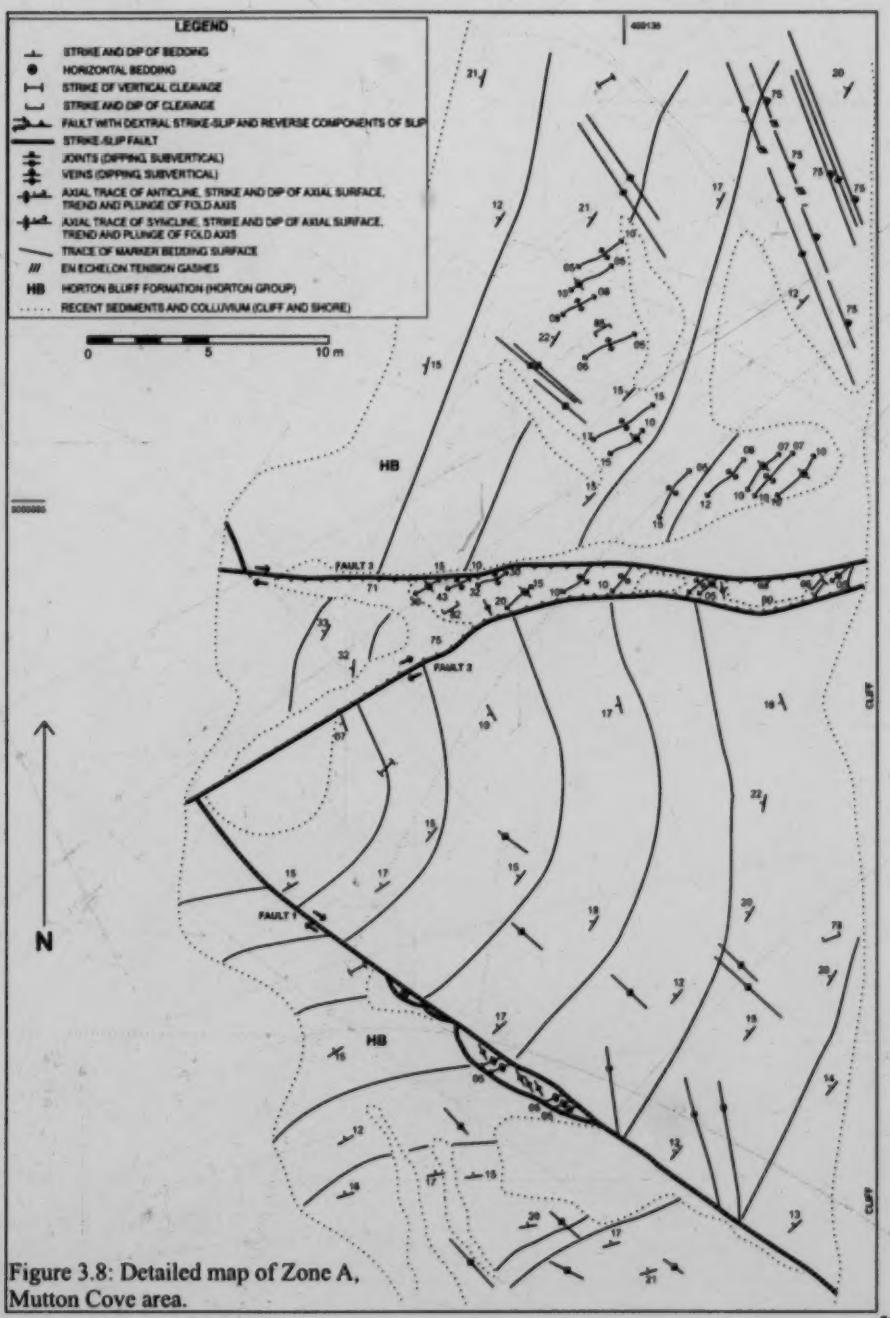

LEGEND
STRIKE AND DIP OF BEDDING
HORIZONTAL BEDDING
STRIKE OF VERTICAL CLEAVAGE
STRIKE AND DIP OF CLEAVAGE
FAULT WITH DEXTRAL STRIKE-SLIP AND REVERSE COMPONENTS OF SLIP
STRIKE-SLIP FAULT
JOINTS (DIPPING SUBVERTICAL)
VEINS (DIPPING SUBVERTICAL)
AXIAL TRACE OF ANTICLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNCLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
TRACE OF MARKER BEDDING SURFACE
EN ECHELON TENSION GASHES
HB HORTON BLUFF FORMATION (HORTON GROUP)
RECENT SEDIMENTS AND COLLUVIUM (CLIFF AND SHORE)
0
5
10 m
N
HB
FAULT 3
FAULT 2
FAULT 1
CLIFF

Figure 3.8: Detailed map of Zone A, Mutton Cove area.

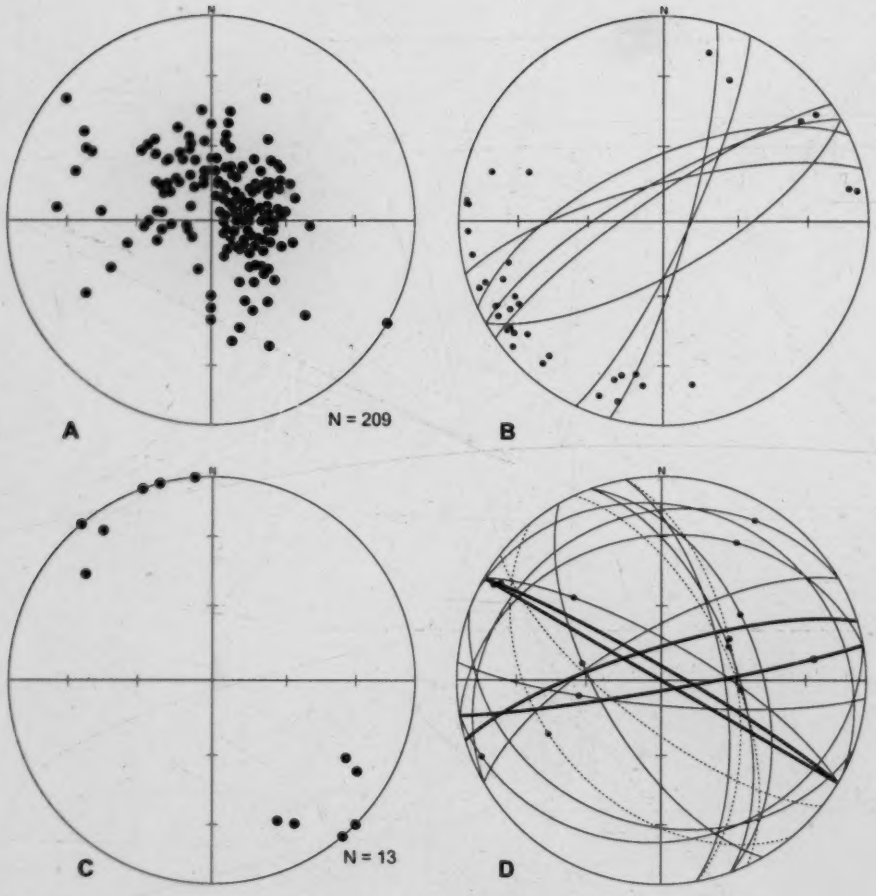


Figure 3.9: Stereographic projections, Mutton Cove area. A) Poles to bedding. B) Measured hinges (dots) and axial planes (great circles). C) Measured cleavage, axial planar to the main folds (dots). D) Strike-slip faults (bold), reverse faults (light), and normal faults (dashed). Small dots represent measured slickenlines.

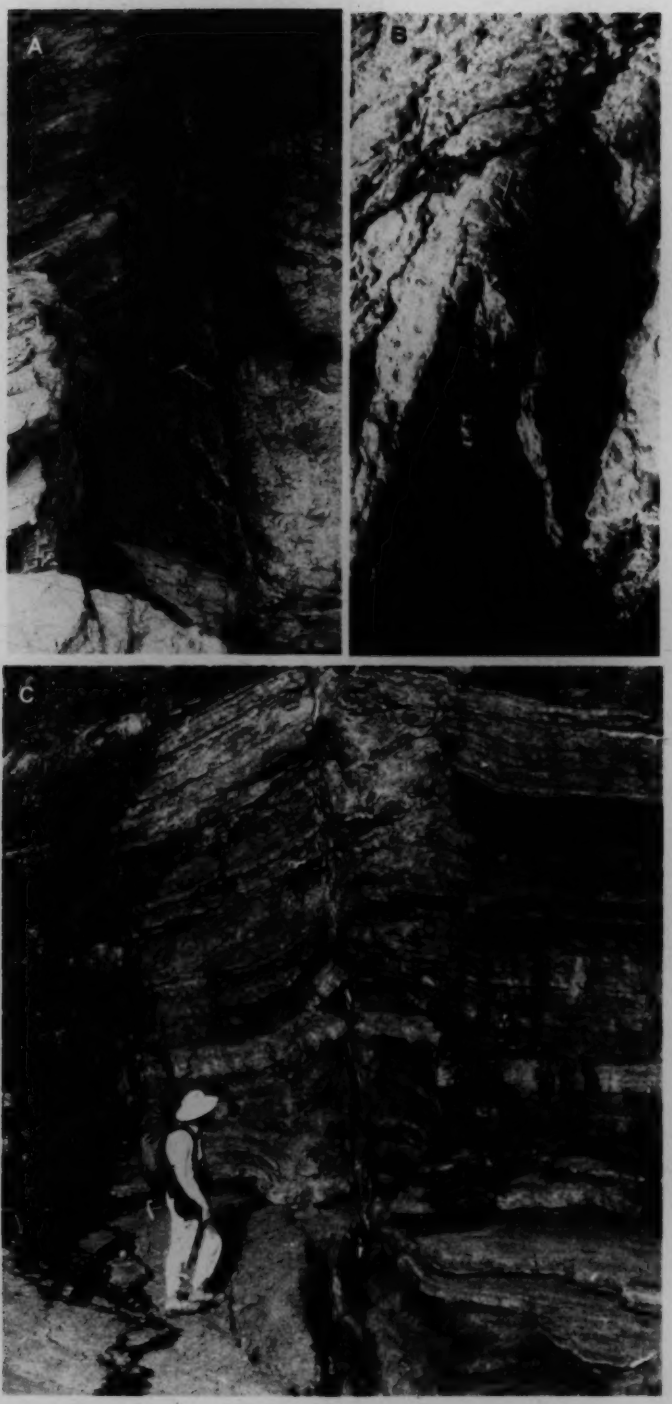


Figure 3.10: Structures observed in the faulting zone, Zone A.

A) Restraining fault bends in Fault 1 contain folds and veins at the centimetre-scale (hammer for scale).

B) Transected cleavage observed in folds near flower structure (pencils for scale, parallel to fold axis and cleavage).

C)Traces of Faults 2 and 3 in the cliff mutually diverge, display strike-slip and reverse displacements. This fault zone is interpreted as a flower structure (person for scale).

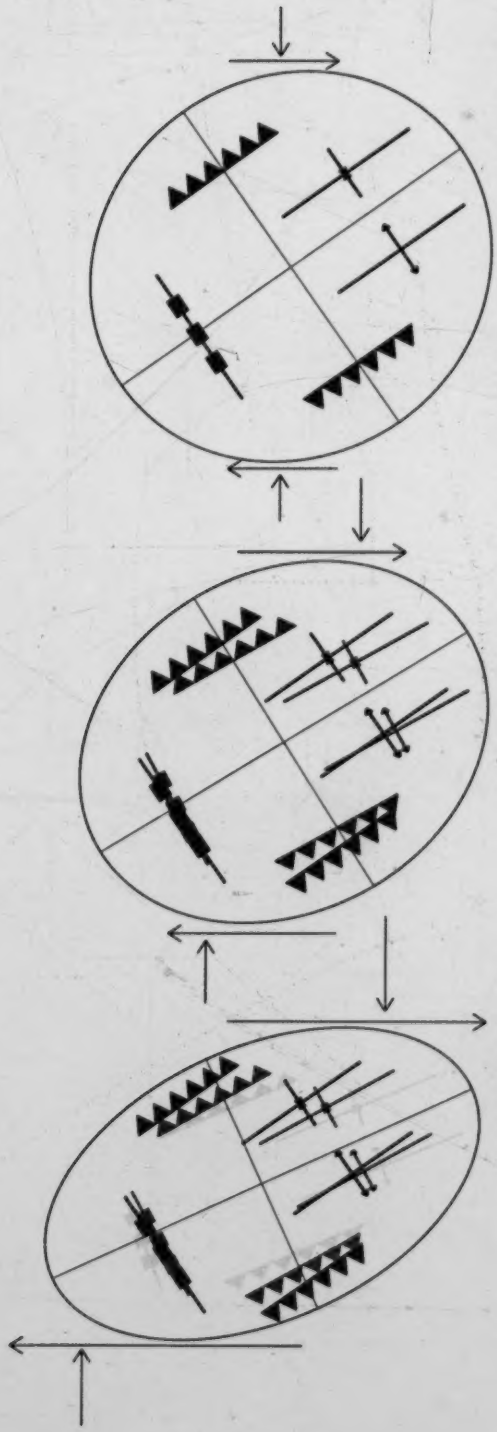


Figure 3.11: Schematic diagram of instantaneous deformation in a transpression zone (not in scale). The development of folds, reverse faults, and extensional veins is shown in different progressive stages.

A) Folds and reverse faults form parallel to the long axis of the instantaneous strain ellipse. Veins and normal faults are perpendicular to the long axis and parallel to the shortening direction.

B) The strike-slip component of the transpression zone rotates the structures previously formed (in grey) whereas new structures (black) are generated as a result of the instantaneous strain at this new stage.

C) As shortening and strike slip continue, new structures develop (black). Structures formed in previous stages display variable strikes (grey, light grey).

3.3. Bass Creek area

The Bass Creek area (Fig. 3.12) extends 300 m west and 500 m east from the mouth of the Bass Brook. Horton Bluff rocks are exposed in the shore and the cliffs, whereas discontinuous exposures of the Wolfville Formation are observed offshore.

3.3.1. Structure

Deformation affects the Horton Bluff Formation in the Bass Creek area. Ripple marks and truncation of foresets observed in Horton strata were used as way-up indicators (Fig. 3.13 A). The orientation of bedding is consistent with the major folds, which plunge gently to the southwest (Fig. 3.14 A). Fabrics are locally developed. Faults were inferred based on bedding separations and outcrop discontinuities.

3.3.1.1. Folds

Folds are open and symmetric, and plunge gently to moderately towards the southwest. Axial surfaces strike northeast-southwest and dip steeply to the northwest or are upright (Fig. 3.14 B). Fold wavelengths are in the order of 25 m. Box folds were recorded in two locations (A1, A2 in Fig. 3.12). These folds occur at the same scale as the open folds described above and their general trend follows the main open folds.

A small number of small-scale folds are exposed in the shore and the cliffs. These outcrops are difficult to access in the cliffs and generally obscured by recent sediments and seaweed on the shore. Small-scale folds are variably oriented, displaying wavelengths from 50 cm to one metre (Fig. 3.13 B). Some hinges in the cliffs appear curved, although measurements to confirm this observation were not made.

3.3.1.2. Faults

Faults in the Bass Creek area were inferred from offsets of sandstone markers and outcrop discontinuities. In addition, air photographs of the area show straight traces defined by outcrop discontinuities on the shore (Fig. 3.12). The traces were observed in the field striking northeast-southwest. Bedding separations recorded in the field and the air photograph are dextral (Fig. 3.12) and range from 5 to 10 metres.

Two sets of joints with different orientations were recorded in the Bass Creek area. One set strikes northwest-southeast and dips steeply to the northeast (Fig. 3.12). The other set of joints strikes northeast-southwest and dips moderately to the southeast.

3.3.1.3. Fabrics

In the Bass Creek area, cleavage is locally developed and it appears penetrative in Horton Bluff shales. Dark fine-grained bands, commonly refracted

from the shale, define this fabric in fine sandstones. Cleavage planes strike northeast-southwest and dip moderately to steeply to the northwest. This orientation is consistent with an axial planar relationship to the large-scale folds (Fig. 3.14 B, C).

On the shoreline near the mouth of the Bass Brook, barrel-shaped boudins were observed in Horton Bluff fine sandstones, surrounded by black shale. Boudins are located in an outcrop-scale shear zone and appear to show elongation in a northeast-southwest direction (Fig. 3.15 A). The shear zone was interpreted as dextral based on the deformation observed in the boudinage. A thin section perpendicular to the boudins was cut, revealing carbonate-filled microveins and stylolites defined by dark clay minerals (Fig. 3.15 B). Stylolites are subvertical and approximately parallel to the direction of extension shown by boudinage (see below). Three sets of microveins were identified in thin section (Fig. 3.15 C, D, E). One set is subvertical and is cut by the stylolites. Another set of veins is also subvertical, but it cross-cuts the stylolites. The third set appears to be oblique to the stylolites and the microveins, apparently disrupting these structures. In order to verify cross-cutting relationships in three dimensions, a surface polished was cut in a plane parallel to the bedding plane (Fig. 3.16 A). It was possible to interpret at least three generation of structures (Fig. 3.16 B). The first generation consists of subvertical microveins that strike northeast-southwest and are cut by stylolites and microveins. The second generation is represented by the subvertical stylolites that strike northeast-southwest. Veins that strike northwest-southeast and are subvertical or dip gently to moderately to the northeast are interpreted as third generation, the latest structures.

3.3.2 Discussion

The most conspicuous structures in the Bass Creek area are the main, large-scale folds, which indicate northwest-southeast shortening. Despite a few observations of curved hinges, overprinting relationships between the large-scale and small-scale folds could not be confirmed.

Faults in the area produced bedding separations, which reveal a component of dextral strike-slip (Fig. 3.12). Although there is no direct evidence that strike-slip is the main component of the faults, the orientation of folds and faults is comparable to the orientations recorded in Mutton Cove (Section 3.2), where both strike-slip faults and folds suggest dextral transpression. The probability that brittle and ductile structures in Bass Creek resulted from dextral transpression is here considered, since the recorded orientations are consistent with this interpretation.

The timing relationship between the described microstructures (Section 3.3.1.3) and the major structures is not known. Boudinage and associated microstructures observed in a zone of dextral shear suggest that shortening occurred locally in about the same orientation as the extension. It is possible that the stylolites were generated later in time, unrelated to the proposed dextral transpression. Another interpretation is offered in Fig. 3.16 C. The first generation of veins, initially perpendicular to the direction of extension, is considered to have been rotated until being subparallel to stylolites formed later in the deformation. In a dextral transpression less rotation would be required than under simple shear, since the

magnitude of shortening is larger than in a simple shear setting. The latest veins are subvertical and strike northwest-southeast; some of them dip gently to the northeast, possibly responding to subvertical extension.

WOLFVILLE FORMATION
HORTON BLUFF FORMATION
HB
BASS
BROOK
A1
A1

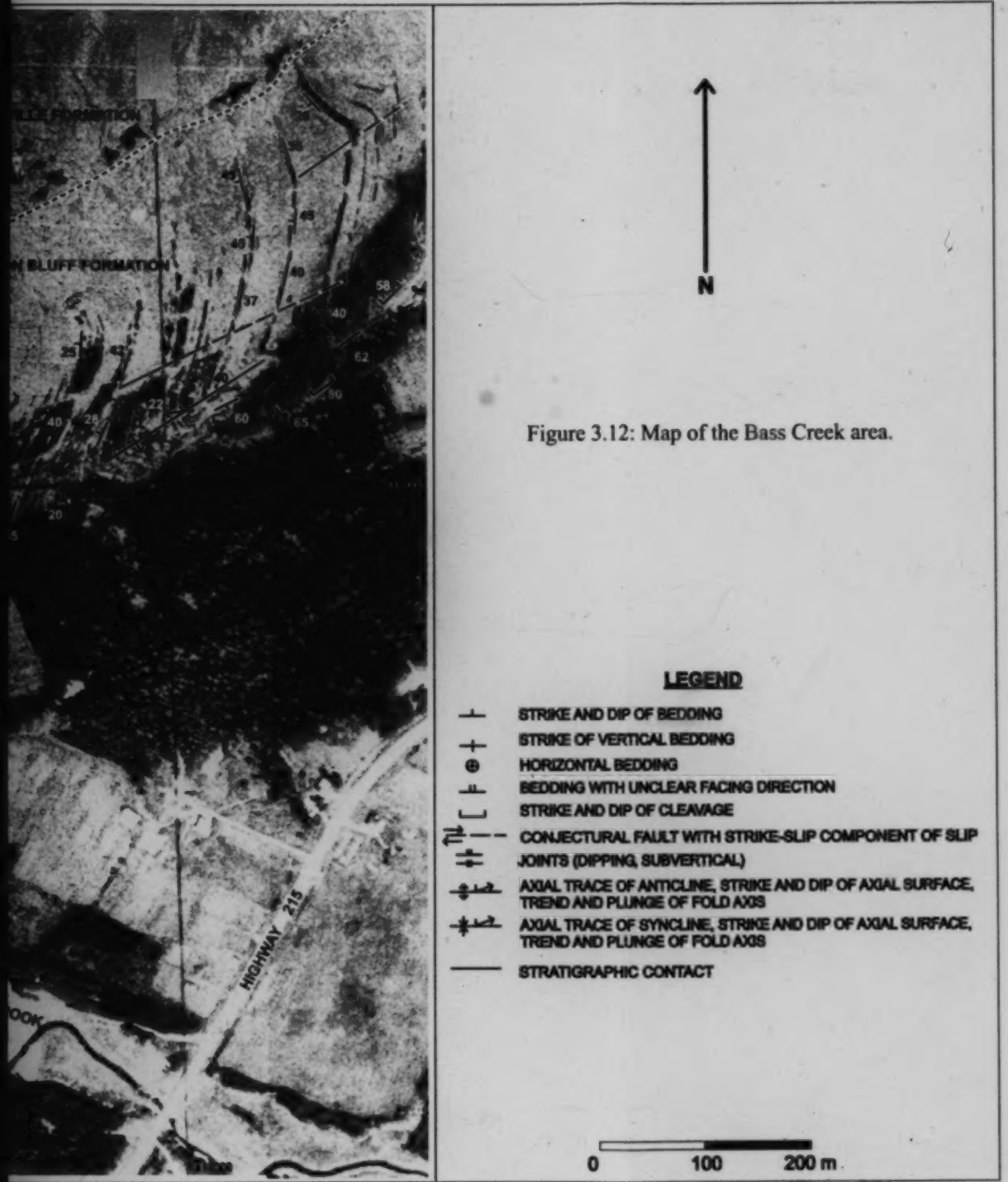

N
BLUFF FORMATION
HIGHWAY 213
LEGEND
STRIKE AND DIP OF BEDDING
STRIKE OF VERTICAL BEDDING
HORIZONTAL BEDDING
BEDDING WITH UNCLEAR FACING DIRECTION
STRIKE AND DIP OF CLEAVAGE
CONJECTURAL FAULT WITH STRIKE-SLIP COMPONENT OF SLIP
JOINTS (DIPPING, SUBVERTICAL)
AXIAL TRACE OF ANTICLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNCLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
STRATIGRAPHIC CONTACT
0
100
200 m

Figure 3.12: Map of the Bass Creek area.

Figure 3.13: Cross-bedded sandstones and associated structures in the Bass Creek area. A) Truncation of foresets was employed as way-up indicator (lens cap for scale). B) Typical quality of F1 fold outcrops, variably oriented in the shore. C) General view of cleavage. Cleavage is penetrative in shale layers and axial planar to the main F2 folds.

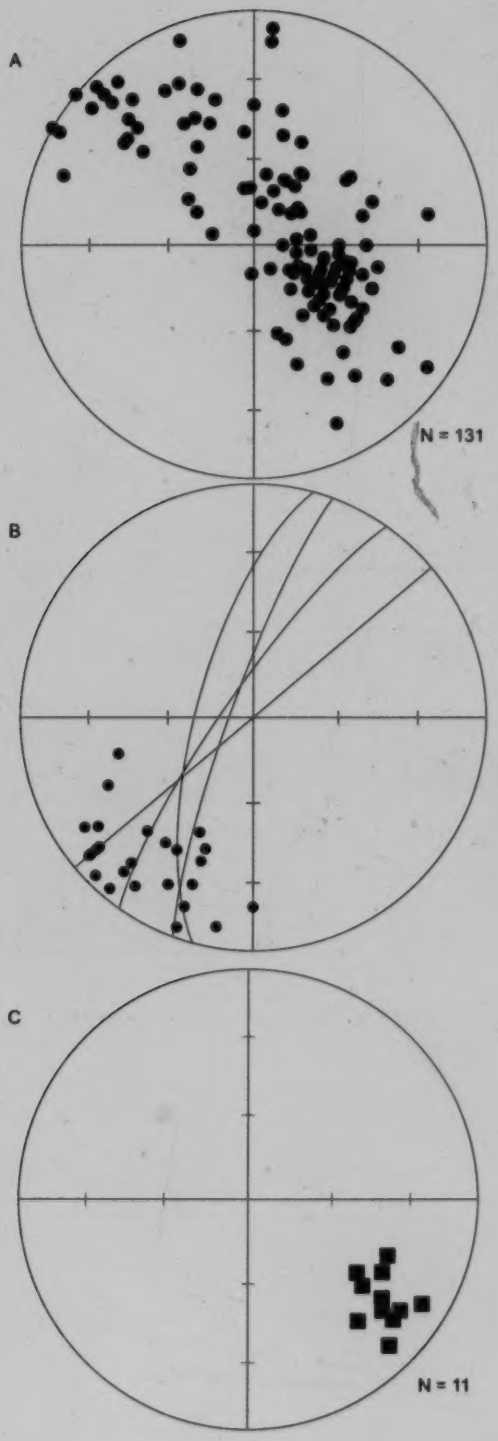


Figure 3.14: Stereographic projections for the Bass Creek area.

A) Poles to bedding (dots) define a girdle oriented northwest-southeast, consistent with the major folds.

B) Measured axial planes (great circles) and hinges (dots) of major folds. Folds plunge gently to moderately to the southwest.

C) Poles to cleavage (square dots). Cleavage planes are axial planar to the main folds.

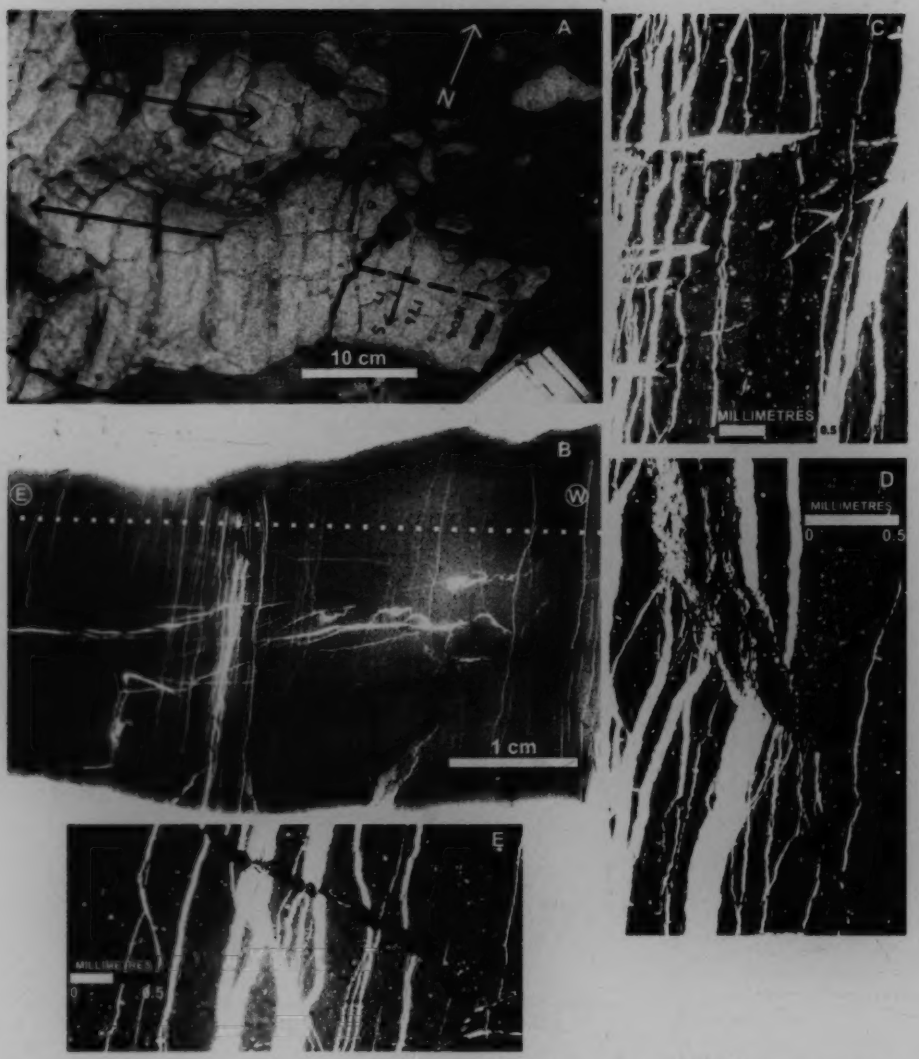


Figure 3.15: Sand boudins observed in the Bass Creek area. A) Final stretching direction is east-west. Solid arrows illustrate dextral shear at outcrop-scale. The dashed line shows the orientation of the thin section. B) High-contrast scan of thin section displaying carbonate microveins and stylolites. Dotted line represents the trace of the plane of bedding (see polished surface parallel to the bedding plane in Fig. 3.16). C, D, E) Microphotographs of thin section showing at least two different sets of subvertical microveins, one set cross-cutting stylolites and the other set being cut by the stylolites. A third set appears oblique and cross-cuts veins and stylolites.

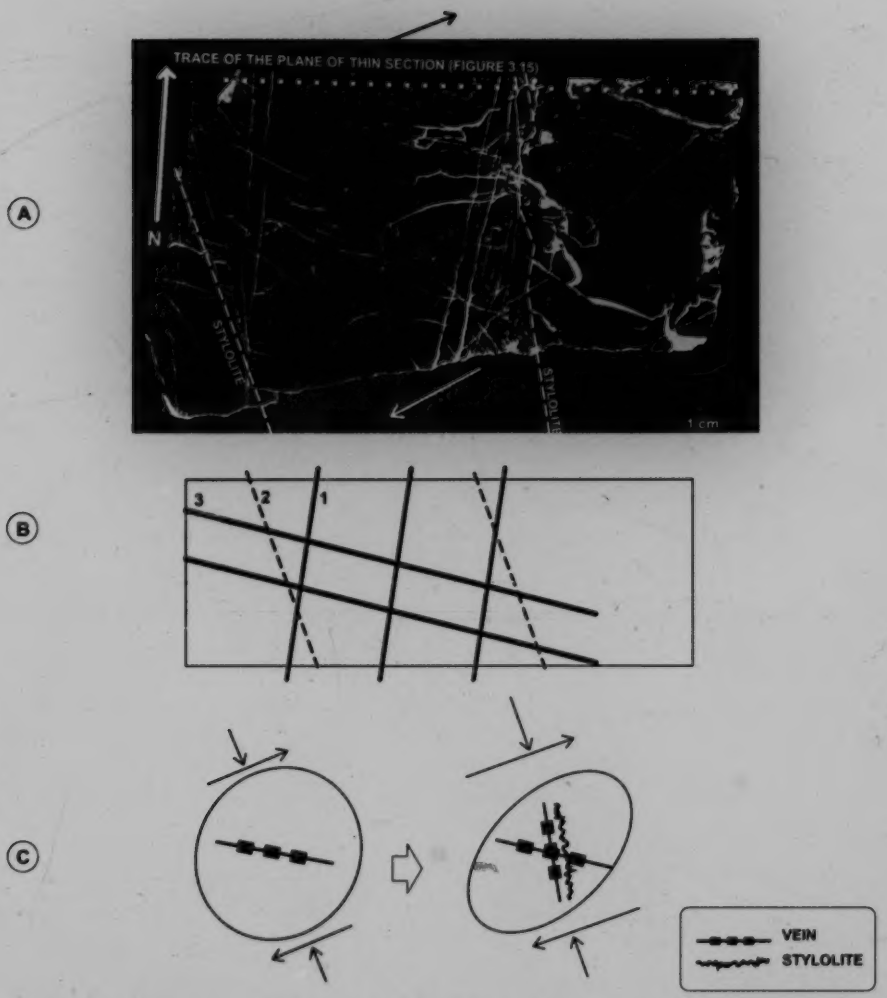


Figure 3.16: Polished surface parallel to the bedding plane of boudinage sample and qualitative kinematic model, Bass Creek area. A) High contrast scan of polished surface; stylolites and the plane of thin section (Figure 3.15) have been highlighted. Arrows (top and bottom) show dextral transpression. B) Interpreted sequence of structures in this surface. Generation 1 (grey) consists of subvertical veins that strike northeast-southwest. Stylolites (dashed lines) striking northwest-southeast are here interpreted as generation 2. The latest structures are veins that strike northwest-southeast, are subvertical, or incline moderately to the northeast. C) Kinematic model for fracture orientation in a transpressional setting. Initially (left ellipse) extensional veins form striking northwest-southeast. In a later stage, veins are rotated (right ellipse, grey) and start closing as shortening increases. Stylolites develop after previous fracture planes (veins). A new set of extensional veins (black) forms striking northwest-southeast, cross-cutting previous veins and stylolites.

3.4. Cambridge Cove area.

The Cambridge Cove area extends about a kilometre to the west and 300 m to the east of the mouth of the Cambridge Creek (Fig. 3.17). The area includes outcrops of the Horton Bluff Formation and the Wolfville Formation. Horton Bluff sandstones contain ripple marks and tree stumps that were employed as way-up indicators (Fig. 3.18). The tree stumps correspond to Lycopsid fossils, identified by Moore (1996) in the nearby area of Bramber, and were employed as local strain markers.

3.4.1. Structure

The Horton Bluff Formation appears strongly deformed in the cliffs and the shore. Folds and faults are well exposed, especially in the west portion. Major folds plunge to the northeast and southwest. Bedding surfaces show a girdle distribution consistent with the major folds (Fig. 3.19 A). Fabrics are locally developed.

Tree stumps (Fig. 3.18) on top of sandstone beds were employed as local strain markers, since their elliptical to circular cross sections can be measured and used to determine the local strain (see Section 6.4.).

3.4.1.1. Folds

Folds are symmetric, open, and plunge gently to moderately to the southwest and northeast (Fig. 3.17, Fig. 3.19 B). Fold wavelengths are about 30 m. Axial

surfaces strike northeast-southwest and are upright, or dip moderately to the northwest. Box folds were observed in the southwest portion of the area, approximately with the same orientation as the main open folds. The scale and geometry of the main folds is comparable to the main folds mapped in Bass Creek (Section 3.3).

A small number of metre-scale folds were observed partially exposed in an area of unstable mud platforms. Fold hinges trend northeast-southwest, but detailed measurements were not obtained.

3.4.1.2. Faults and veins

A number of faults planes were observed in the cliffs, most of them striking northeast-southwest and dipping moderately to the northwest (Fig. 3.17). Apparent offsets range from 2 to 8 metres. Bedding separation and poorly developed slickenlines with carbonate fibres indicate reverse slip.

In addition, straight lineaments were observed on the shore and the air photograph of the mapping area (Fig. 3.17). These lineaments are about 100 metres long and consist of straight zones of bedding separation trending northeast-southwest. Bedding separations are dextral and range from 5 to 10 metres. No slickenlines could be documented.

En echelon and sigmoidal veins striking north-south and east-west were recorded on the shore (Fig. 3.20 A, B, C). Veins range from 0.5 to 1 cm thick and are

filled with quartz. En echelon and sigmoidal geometries were attributed to shear zones, which are interpreted in Section 3.4.2.

Most of the mapped joints are subvertical and strike northwest-southeast; a minority of them strike northeast-southwest.

3.4.1.3. Fabrics

Cleavage is locally developed, strikes northeast-southwest, and dips moderately to the northwest. Shales display penetrative cleavage, in some cases refracted into sandstone beds as dark clay-rich, non-penetrative domains. These fabrics are axial planar to the main F2 folds (Fig. 3.19 C).

Fossil tree stumps were observed in fine sandstones of the middle member of the Horton Bluff Formation. They display distorted sections from circular to elliptical. More than 130 were documented as potential strain markers, measuring the long and short axes of ellipses, and recording the trend of the long axis for each specimen. The purpose of the study was to determine the local strain (see Section 6.4.).

3.4.2. Discussion

The distribution of bedding is in general consistent with the orientation of the main folds. Axial planar cleavage appears undisturbed throughout the area. The

orientation of the main folds is consistent with a northwest-southeast shortening (Fig. 3.19, Fig. 3.17). Although metre-scale folds could not be properly recorded, the orientation of the fold hinges is similar to those of the main folds.

Straight traces of faults in the area show a component of dextral strike slip (Fig. 3.17). The mapped reverse faults commonly strike northeast-southwest, again suggesting a northwest-southeast direction of shortening.

En echelon and sigmoidal veins observed in the central part of the area were interpreted as the result of transpression and progressive deformation (Fig. 3.20 D). Tension gashes were initially formed at less than 45° to the direction of shear and were progressively rotated during subsequent deformation. The interpreted sinistral shear zones are oriented north-south, whereas the dextral shear zones are oriented east-west.

Circular and elliptical sections of tree stumps were studied in the central part of the area. The Rf/f plot (Ramsay, 1967; Ramsay and Huber, 1983) assumes that the tree stump sections were randomly oriented and were not necessarily circular prior to the deformation. The rock volume is considered to have remained constant. The assumed strain is homogeneous and planar. For each deformed object on a planar surface, the ratio of the long axis of the ellipse to the short axis is measured. This ratio, called Rf or ellipticity, is plotted versus the orientation of long axes of the ellipses (f). In this case, the resulting cluster establishes a mean northeast-southwest long axis of the final strain ellipse (Fig. 3.21). In order to determine the finite strain value Rs, the strain marker distribution was compared to standard grids for different

values of Rs (Leslie, 1985). The best-fit set of curves corresponds to Rs=1.15 (Fig. 3.21).

In summary, the orientations of the main faults and folds indicate a northwest-southeast shortening. Dextral strike slip components oriented northwest-southeast are shown by faults. The strain markers indicate a strain axis S1 that is very close in orientation to the fold hinges and the strike of cleavage planes. The orientation of the main structures and the strain markers are consistent with a dextral transpression setting in this area.

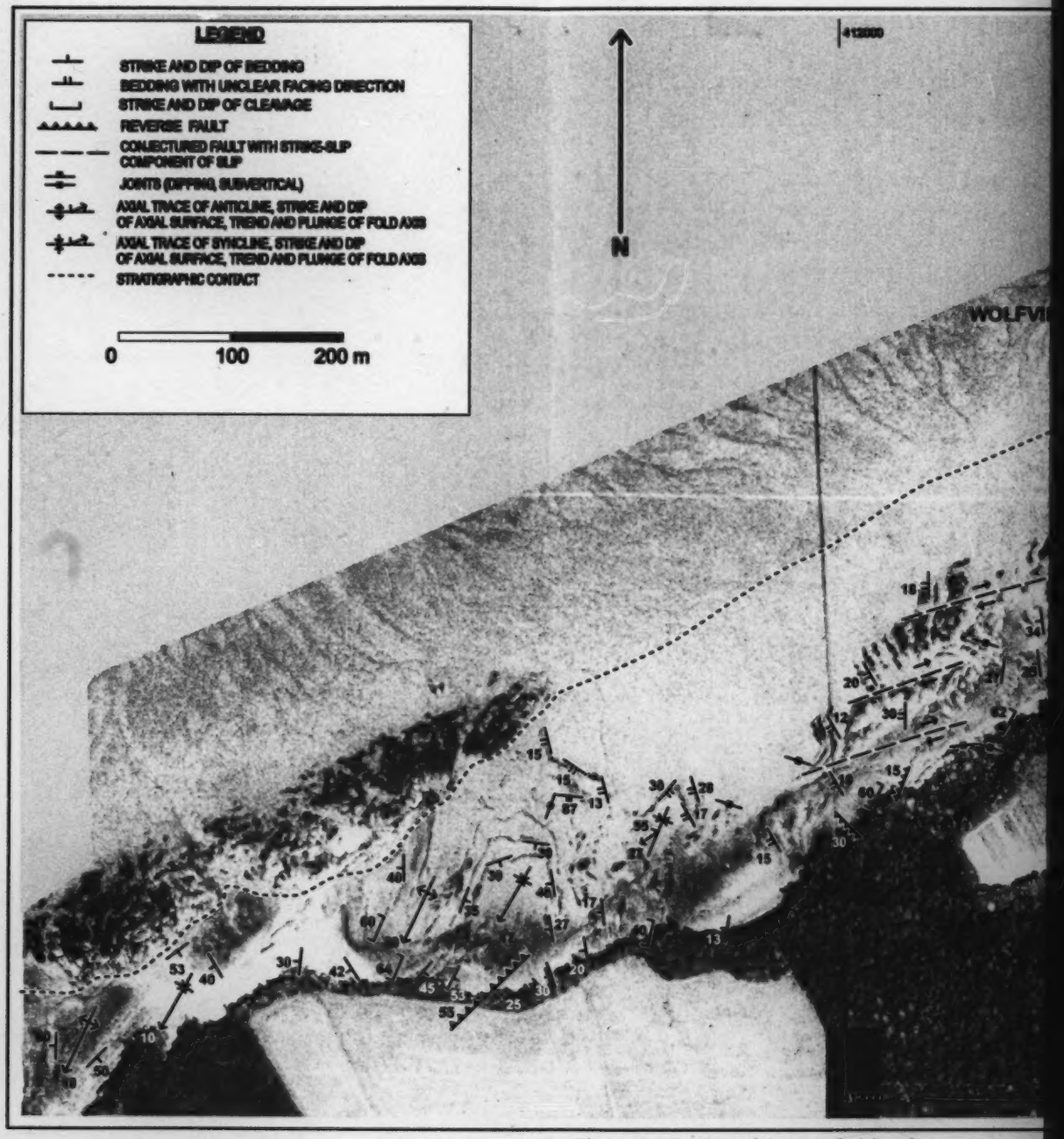

LEGEND
STRIKE AND DIP OF BEDDING
BEDDING WITH UNCLEAR FACING DIRECTION
STRIKE AND DIP OF CLEAVAGE
REVERSE FAULT
CONJECTURED FAULT WITH STRIKE-SLIP COMPONENT OF SLIP
JOINTS (DIPPING, SUBVERTICAL)
AXIAL TRACE OF ANTICLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNCLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
STRATIGRAPHIC CONTACT
0
100
200 m
N
WOLFVI

Figure 3.17: Map of the Cambridge Cove area.

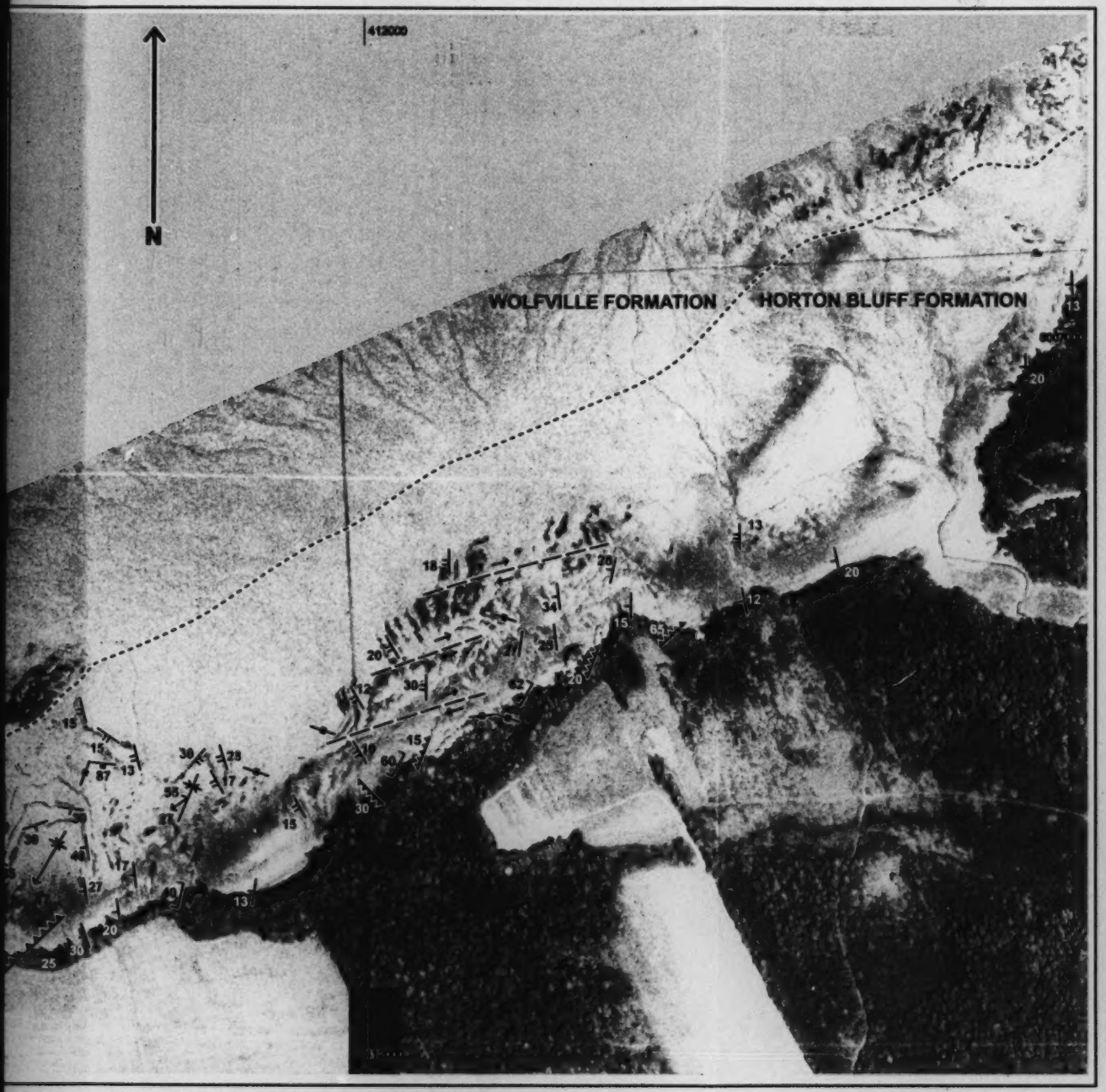


Figure 3.17: Map of the Cambridge Cove area.

Figure 3.18 : Elliptical transverse sections of tree stumps on the shore of Cambridge Cove, employed as strain markers (triangular arrows, lens cap for scale in upper photo). Strain ellipse obtained from strain analysis (see Figure 3.21) is shown in upper photo.

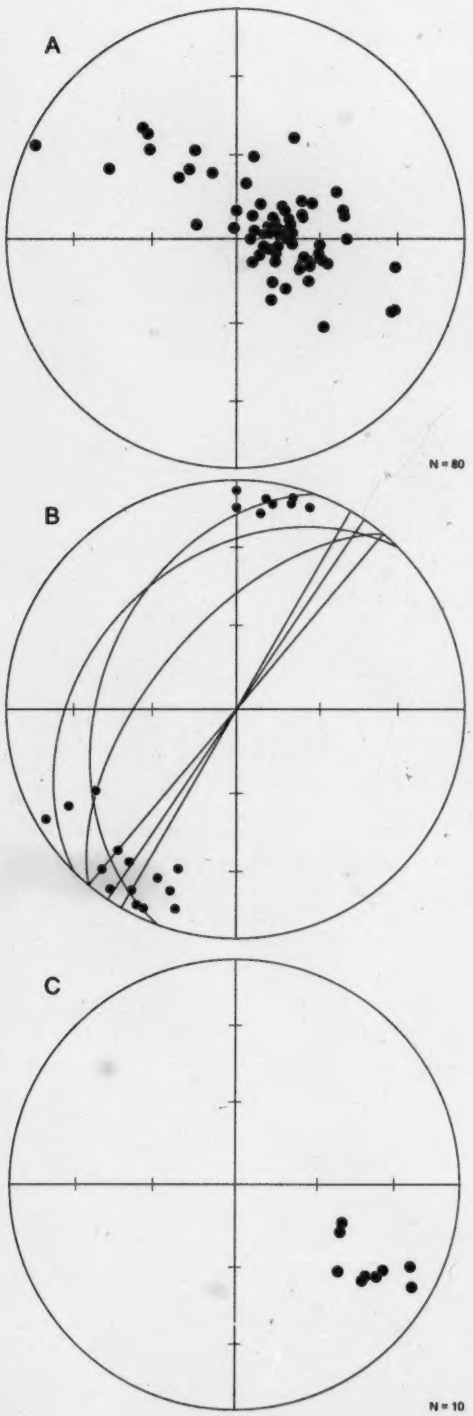


Figure 3.19: Stereographic projections for the Cambridge Cove area.

A) Poles to bedding (dots) are distributed about a northwest-southeast girdle.

B) Measured axial planes (great circles) and hinges of major folds (dots). Folds plunge gently to moderately to the southwest and northeast.

C) Poles to cleavage planes (dots), axial planar to the main folds.

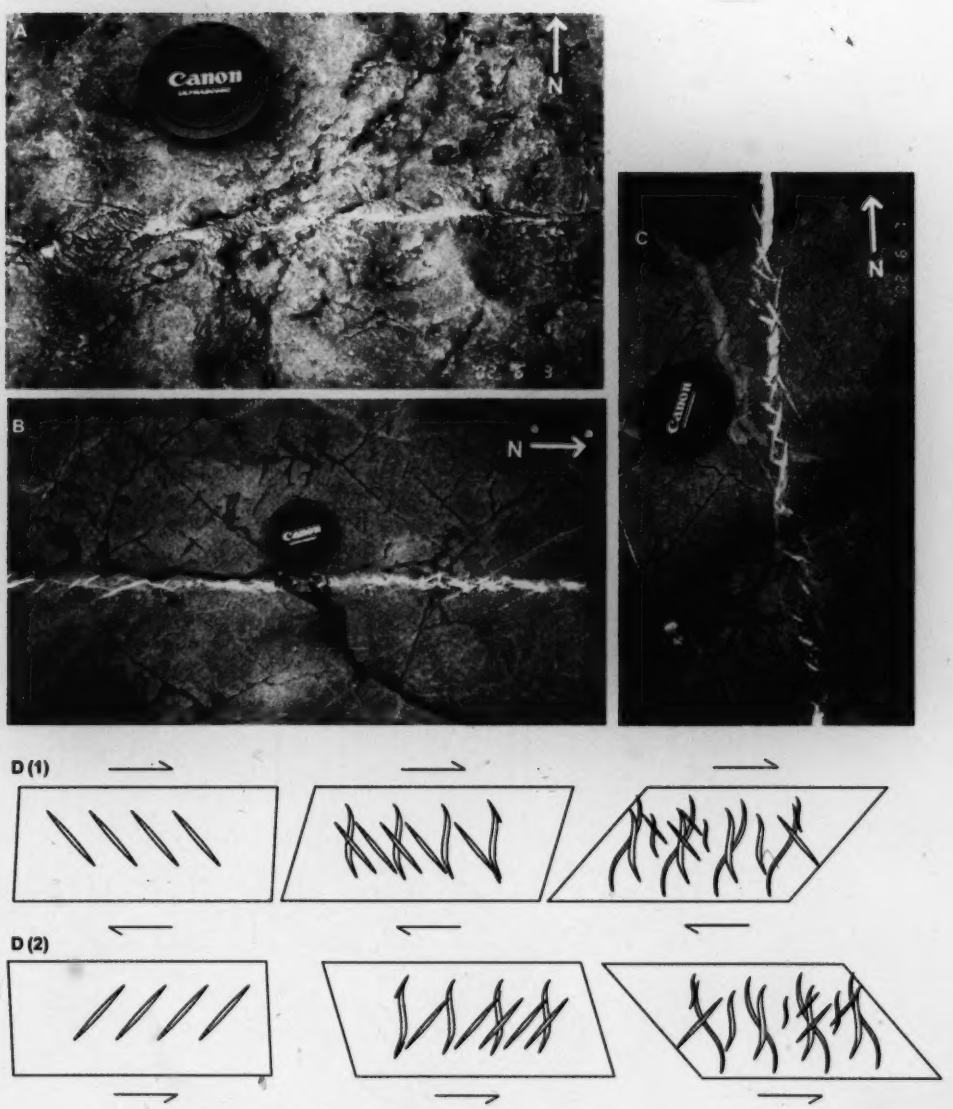


Figure 3.20: En echelon quartz veins, Cambridge Cove area.

A) Sigmoidal quartz veins, defining dextral shear zone oriented east-west (lens cap for scale).
B, C) Examples of en echelon quartz veins. These veins define sinistral shear zones striking north-south (lens cap for scale).
D) Model for progressive formation and folding of veins in dextral (1) and sinistral (2) shear zones. Tension fractures progressively rotate in the direction of shear and later veins form in the original orientation (modified from Davis and Reynolds, 1996).

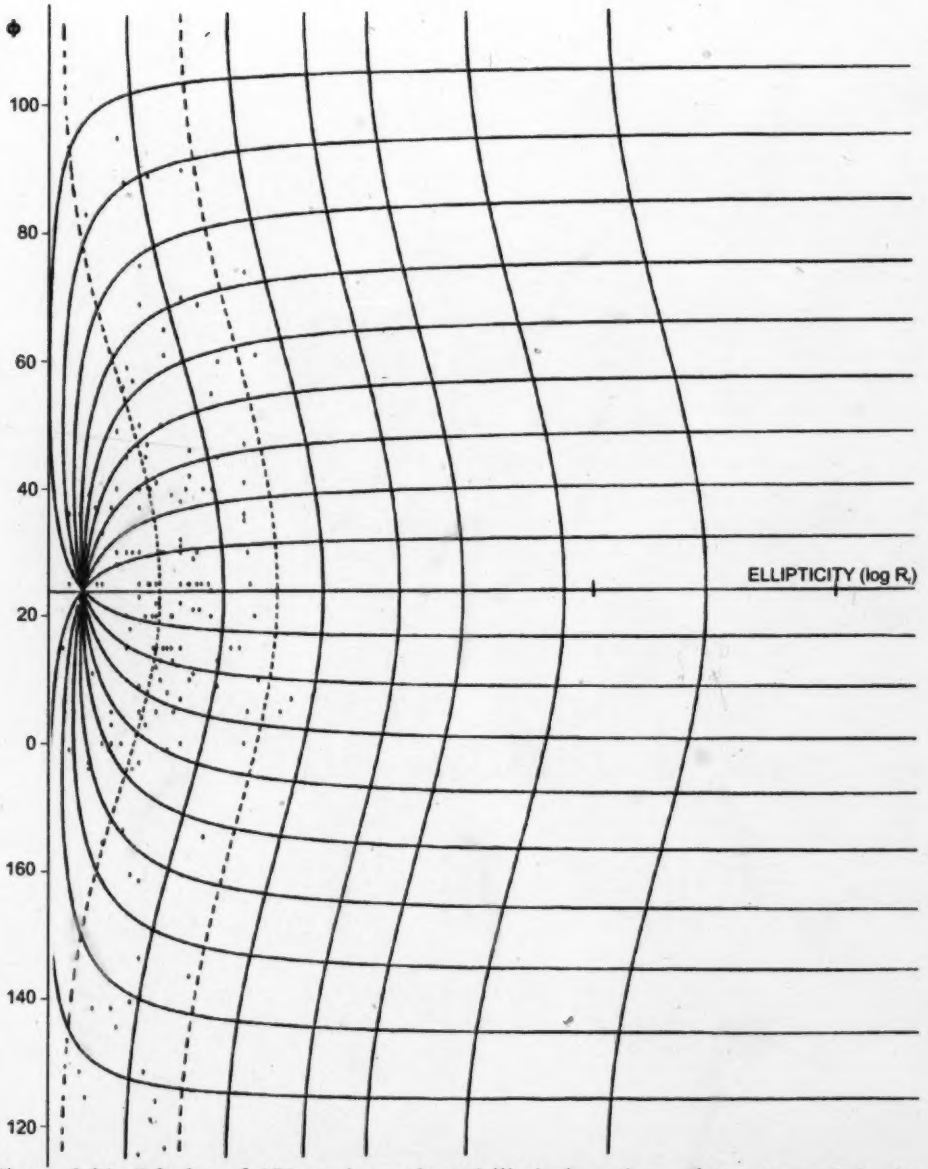


Figure 3.21: Rf plot of 171 strain markers (elliptical sections of tree stumps) in the Cambridge Cove area. The ratio of the long axis of the ellipse to the short axis (ellipticity) is plotted versus the orientation of long axes of the ellipses. Long axis of finite strain is defined by a cluster oriented about 25^{O} of azimuth. The marker distribution was superimposed to standard curves for different strain ratios, being the grid for Rs=1.15 the best-fit set of curves. (Marker deformation grid after Lisle, 1985).

3.5. Little Rainy Cove Area

The Little Rainy Cove area extends from the east portion of the Cambridge Cove area to the west margin of Rainy Cove Brook (Fig. 3.22, Fig. 3.23).

The exposed sections correspond to the Horton Bluff Formation and the Wolfville Formation. The contact between the Triassic Wolfville Formation and the Mississippian Horton Bluff Formation is unconformable. Based on the degree of exposure and deformation, the map has been divided into two main A (west) and B (east) sectors (Fig. 3.22 and Fig. 3.23, respectively). In Sector A, the Horton Bluff Formation is largely obscured by Wolfville Formation sandstones. Horton Bluff strata show a low degree of deformation with respect to Sector B, which contains very good exposures folds, faults and fabrics affecting Horton rocks.

3.5.1. Structure

In Sector A, the Horton Bluff Formation appears as a poorly exposed homoclinal succession that strikes northeast-southwest and dips moderately to the northwest (Fig. 3.22). Post-Triassic normal faults were occasionally observed.

In Sector B, the Horton Bluff Formation appears strongly deformed in the cliffs and in the shore. Overturned folds are the most conspicuous structures in this subarea (Fig. 3.23). Some hinges in the cliffs display variable orientations and are probably refolded (see below). Most of the faults show reverse separation of strata, and are oriented north-south or northwest-southeast. Cleavage is locally developed, and was observed folded near Little Rainy Cove Brook (Section 3.5.1.3). The

orientations of cleavage surfaces and faults are in sharp contrast with previous areas (Sections 3.2, 3.3, and 3.4). In some folded sandstone beds, convolute lamination and hydroplastic deformation structures were observed (Fig. 3.24 A).

3.5.1.1. Folds

In Sector B, most folds are asymmetrical, tight, overturned, and plunge moderately to the south or southwest (Fig. 3.23, Fig. 3.25 A, B). Fold wavelengths range from 40 to 80 m. Axial surfaces strike northwest-southeast and dip steeply to moderately to the southwest. In sandstone layers, folds can be best described as Class 1B or 1C of Ramsay (1967). A geometry corresponding to Class 3 (Ramsay, 1967) is shown by the folded shale layers. Second-order anticlines and synclines that display orientations similar to the main folds appear occasionally in the cliffs.

In the cliffs and the shore, variably oriented, metre-scale wavelength folds with refolded hinges are observed (Fig. 3.24 A, B, C). Fine sandstone layers are internally deformed, showing convolute lamination and load structures. These folds are intrafolial, being observed within the limbs of major overturned folds. Some of the best examples crop out high in the cliffs and therefore were not recorded. However, a number of folded axial surfaces and hinge measurements were taken on the shore. Stereoplots of these measurements do not show any specific pattern (Fig. 3.25 D, E).

Overprinting relationships between the major overturned folds and the small-scale intrafolial folds are not obvious. Because of their refolded hinges and the fact that they do not affect the axial planes or the cleavage of the major folds, the small-scale folds are thought to predate the main overturned folds. The small-scale folds

are therefore designated F1, whereas the large-scale, overturned folds, are designated F2.

3.5.1.2. Faults

In Sector A, faults strike northeast-southwest and dip steeply to the northwest and southeast (Fig. 3.22). Bedding separations are normal and range from 2 to 10 metres. These faults affect both Wolfville and Horton Bluff strata; therefore they are post-Triassic. Joints are rare and are variably oriented.

In Sector B, most of the observed faults are reverse, strike northwest-southeast and north-south, and dip moderately to the southwest and the west (Fig. 3.23). Slickenlines, defined by calcite fibres and grooves, indicate reverse displacements. In the cliffs, apparent offsets of bedding range from 2 to 5 meters.

3.5.1.3. Fabrics

In Sector B, locally developed slaty cleavage strikes northwest-southeast, and dips moderately to the southwest. It is axial planar to the main F2 folds (Fig. 3.25 C, Fig. 3.26 A) and can be attributed to the same strain that generated the F2 generation of structures.

In Sector B, near the mouth of Little Rainy Cove Brook, folded cleavage surfaces were observed in an interval of sandstones and paleosols (Fig. 3.27). In this area, cleavage seems to have been folded about an axis that plunges to the southwest, though much less tightly than bedding in the same area (Fig. 3.27).

Regionally, the cleavage planes measured in this area intersect in the southwest quadrant, suggesting a general folding of cleavage after southwest-plunging axes (Fig. 3.25 C).

3.5.2. Discussion

The orientation of major folds and faults in Little Rainy Cove clearly contrast with those measured in areas to the west (Section 3.2, 3.3, and 3.4). The structures are not in the orientation expected for a dextral transpression along the south shore of the Minas Basin (northeast-southwest direction) as was proposed in previous sections. Only the L2 hinges of the F2 folds, plunging moderately to steeply towards the southwest, are consistent with a simple dextral transpression model.

The folding of S2 axial planar cleavage is indicative of a third episode of deformation. Field observations and stereoplots of S2 cleavage (Fig. 3.25 C) suggest that F2 structures were reoriented by another generation of folds, F3. The regional attitude of cleavage shows a large-scale folding after southwest-plunging axes. Fig. 3.26 B and C show some degree of refolding of second order F2 folds in the cliffs. Observations made farther east, in Rainy Cove and Walton areas (Section 3.6 and 3.7) support the idea of a third generation of structures.

At a smaller scale, L1 hinges and axial surfaces show a dispersed pattern (Fig. 3.25 D). If the interpretation presented here is correct, the F1 folds were refolded by F2 and F3 folds. The observed pattern could be the result of complex interference patterns of three generations of structures. Another possibility is that the F1 folds

were formed in a hydroplastic deformation environment, as suggested by convolute lamination, and the resulting folding did not assume a specific pattern.

The girdle distribution shown by bedding surfaces is approximately consistent with a mean south-southwest-trending L2 axis (Fig. 3.25 A). The girdle appears somewhat dispersed, due to large-scale F3 folds.

It is possible that the F3 generation of structures reoriented the faults (Fig. 3.23). The expected orientation of faults for a dextral transpression is opposed to what has been documented.

Mesozoic normal faults observed in Sector A are rare and small, and the amount of deformation is small. Their orientation is consistent with sinistral motion along the Cobequid Fault, as proposed by Mawer and White (1986).

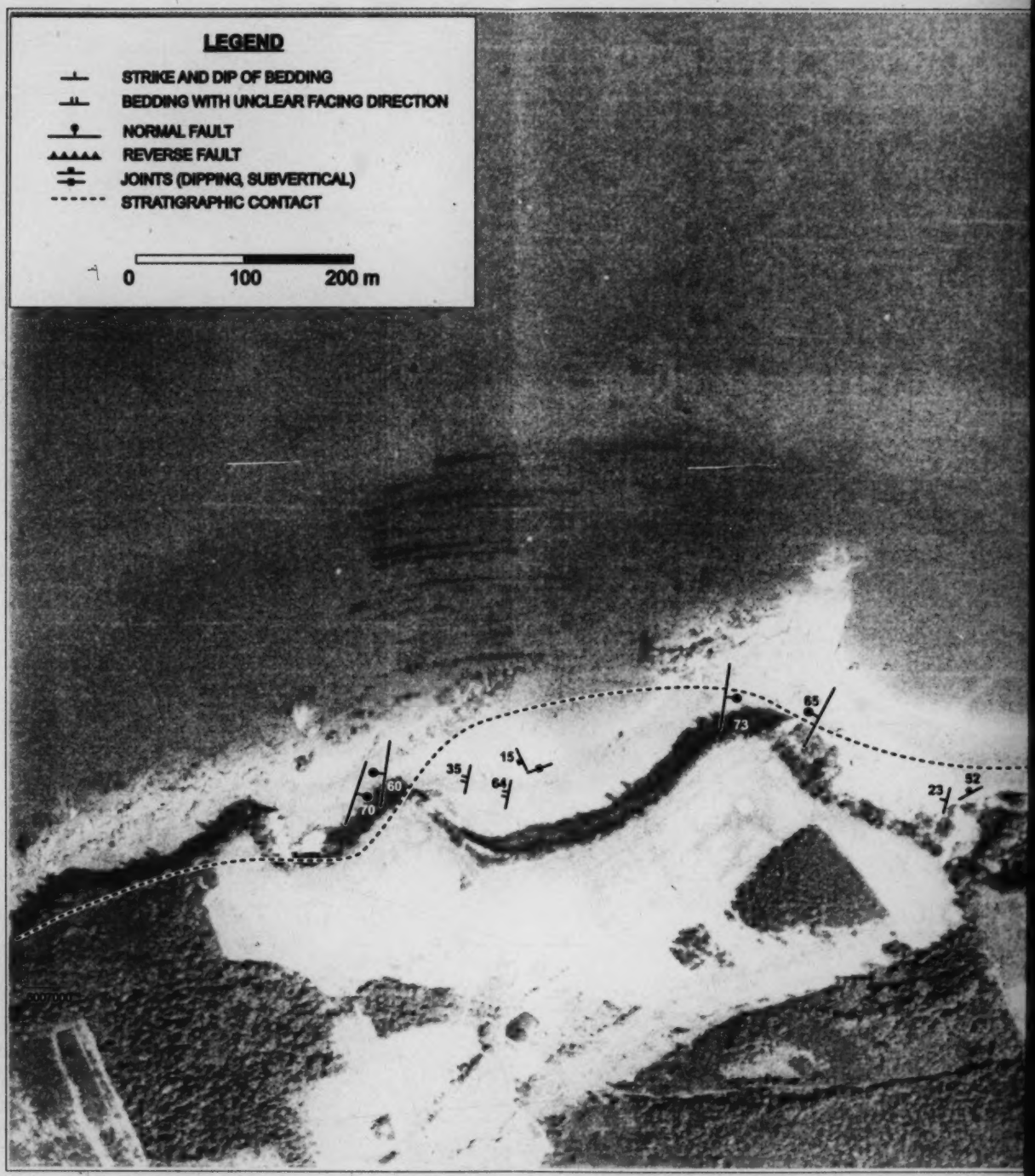


Figure 3.22: Map of the Little Rainy Cove area, Sector A.

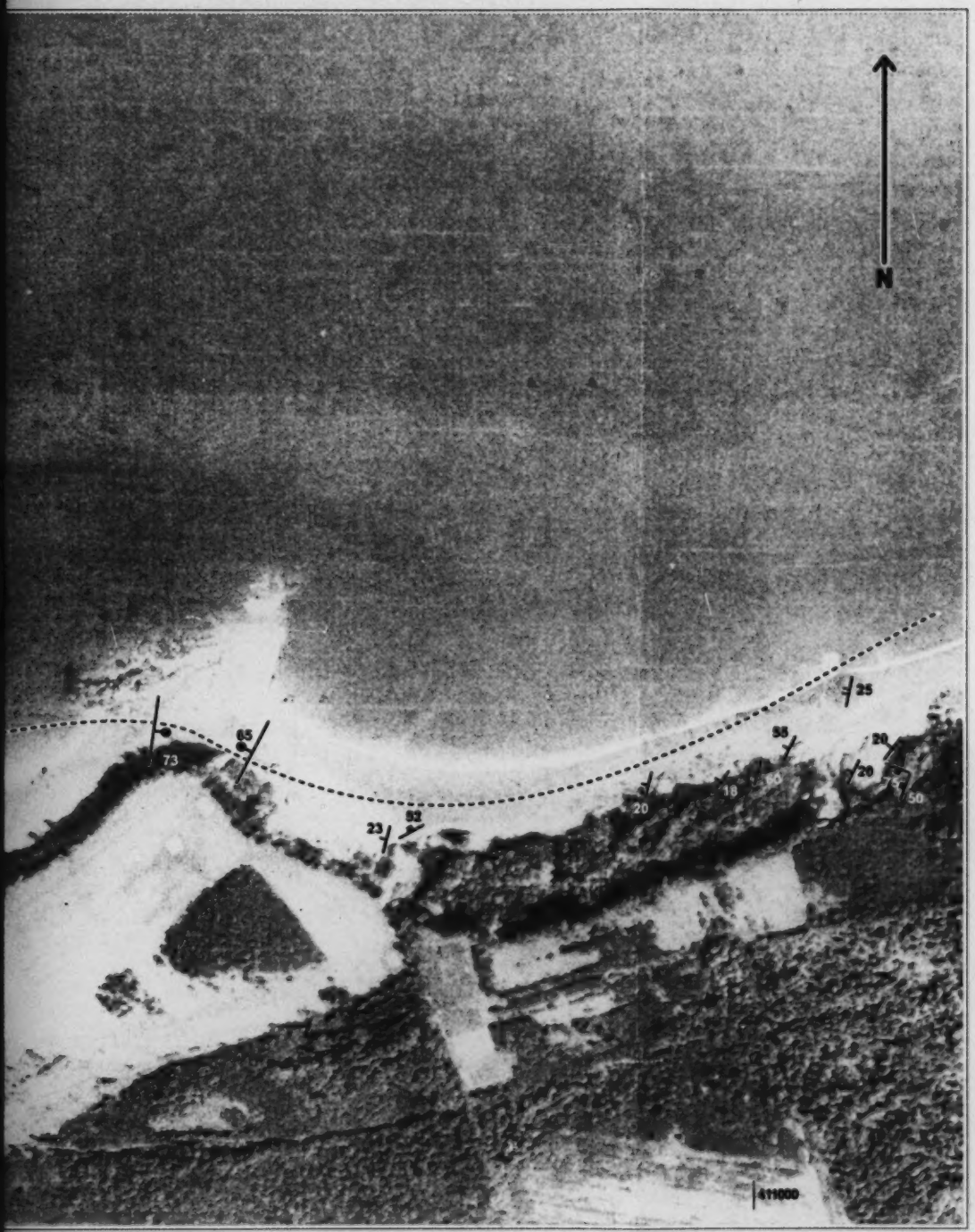
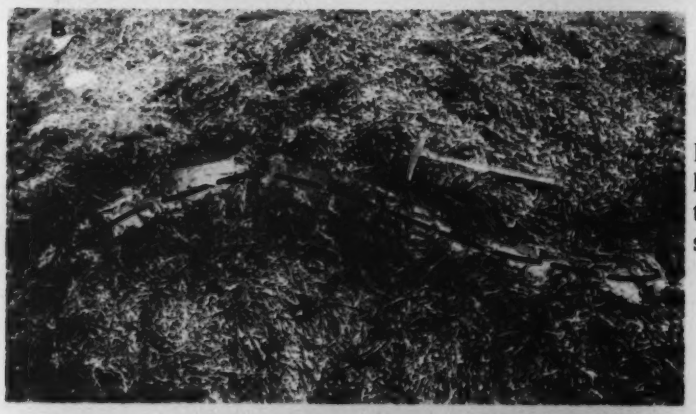

N
73
65
23
22
20
18
55
25
20
20
50
411000

Figure 3.23: Map of the Little Rainy Cove area, Sector B.

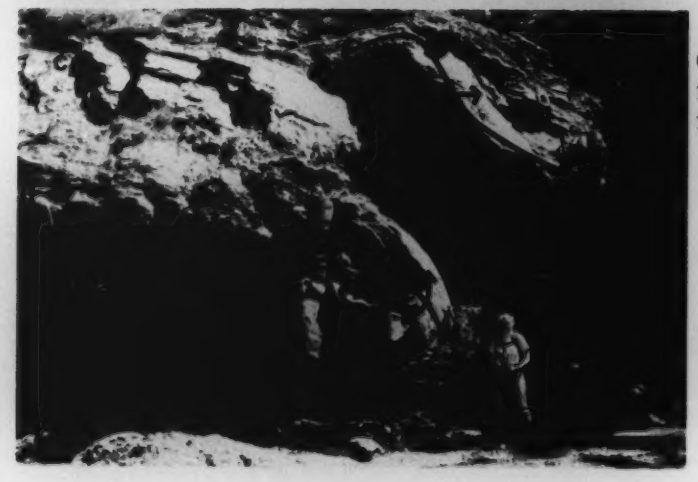
RAINY COVE BROOK
HORTON BLUFF FORMATION
Figure 3.28 B
Figure 3.28 C
HIGHWAY 215
LEGEND
STRIKE AND DIP OF BEDDING
BEDDING WITH UNCLEAR FACING DIRECTION
STRIKE AND DIP OF OVERTURNED BEDDING
STRIKE AND DIP OF CLEAVAGE
REVERSE FAULT
JOINTS (DIPPING, SUBVERTICAL)
AXIAL TRACE OF OVERTURNED ANTICLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF OVERTURNED SYNCLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
0
100
200 m

Figure 3.24: F1 folds and associated structures in the Little Rainy Cove area.

A) Convolute lamination and hydroplastic deformation structures in fine sandstone folded beds (lens cap for scale).



B) Typical folded L1 hinge (dashed line) on the shore (hammer for scale).



C) Variably oriented F1 folds in the cliff (person for scale).

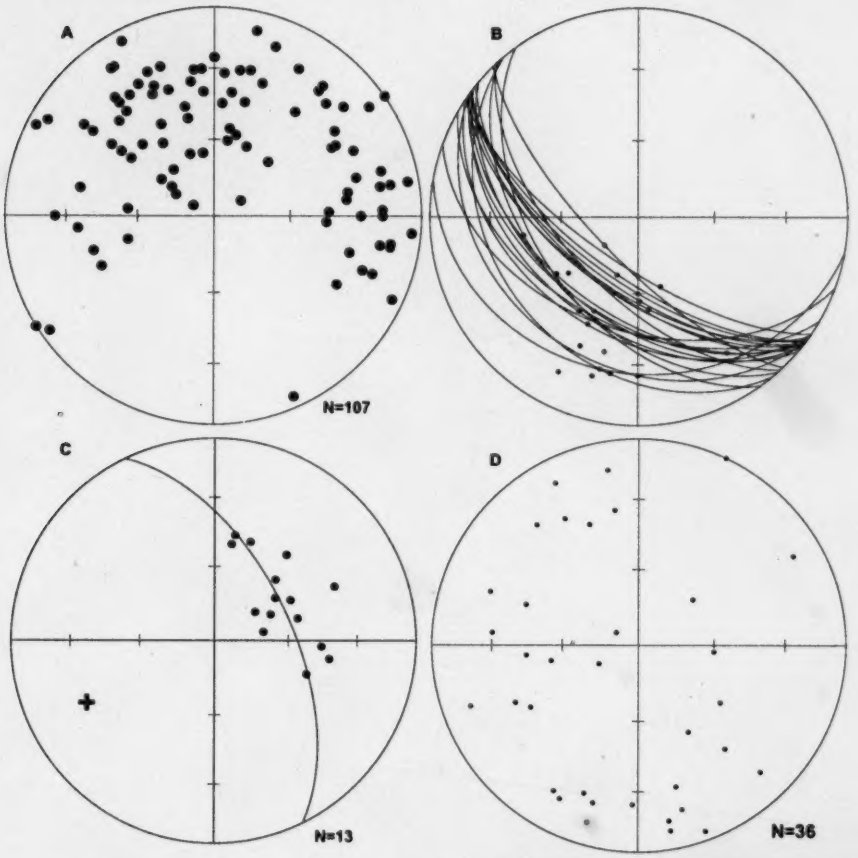


Figure 3.25: Stereoplots, Little Rainy Cove area. A) Poles to bedding displaying a girdle distribution after a south to southwest-plunging axis. The girdle appears lightly dispersed, possibly due to large-scale refolding. B) Axial planes (great circles) and fold hinges (dots) of the F2 folds, the major structures in the area. C) Poles to S2 cleavage (dots) are distributed in a girdle about a southwest-plunging axis ('+' symbol). D) L1 hinges (dots). E) Poles to axial planes (dots) of the F1 folds. Measured hinges and axial planes of F1 folds do not show any specific pattern in this area. Possible interpretations are offered in Section 3.5 (see text).

Figure 3.26: F2 fold geometries and associated fabrics in the Little Rainy Cove area.

A) Axial planar cleavage S2 (solid lines) in major F2 fold in the cliff (person for scale). F2 folds are overturned and plunge moderately to the southwest. Cleavage in this case strikes northwest-southeast and dips moderately to the southwest.

B) Second-order F2 folds in the cliffs, showing gentle refolding possibly due to F3 folds (dashed lines represent axial traces).

C) Fold interference pattern, possibly a second-order F2 fold, refolding F1 folds in the cliff (dashed lines represent axial traces). S2 cleavage (solid lines) is strongly refracted in sandstone layers.

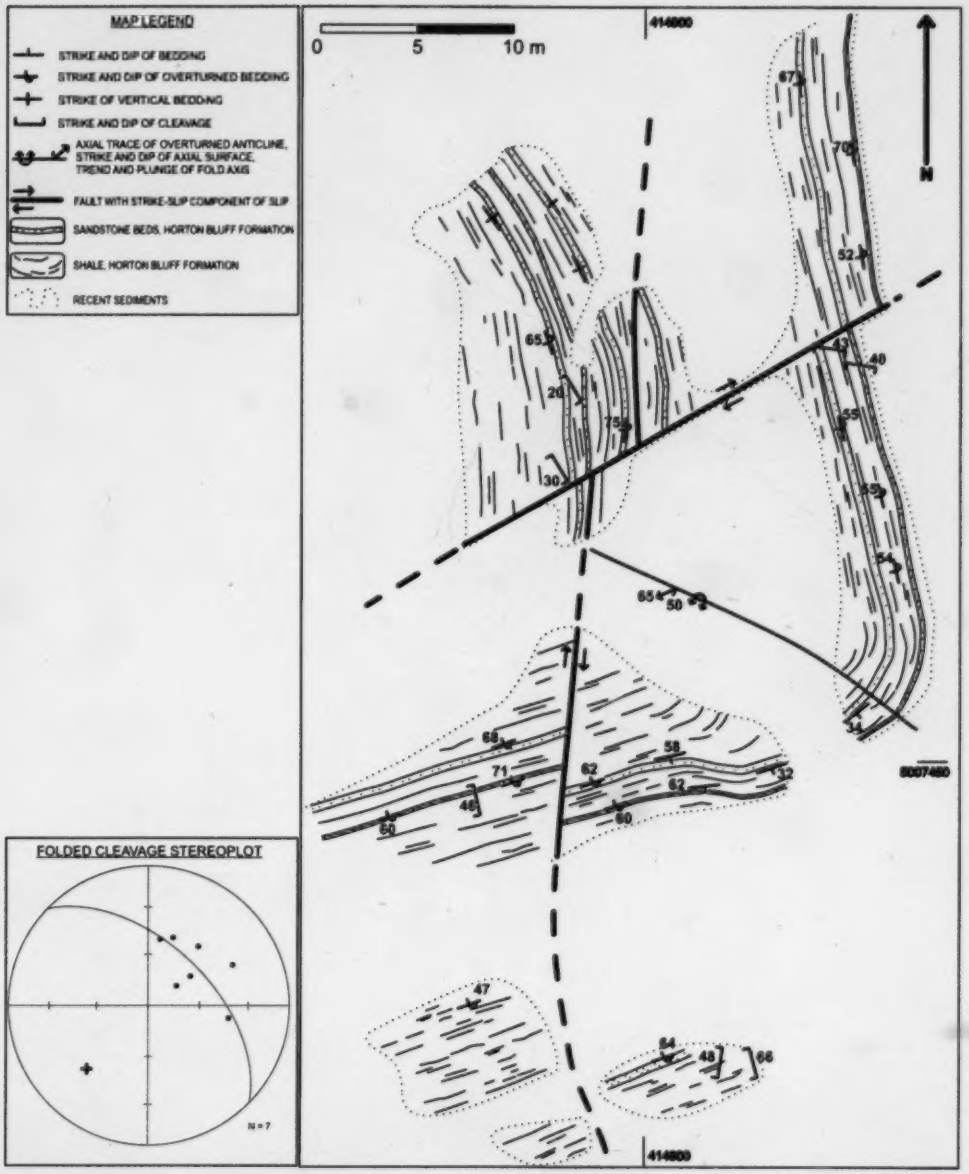

MAP LEGEND
STRIKE AND DIP OF BEDDING
STRIKE AND DIP OF OVERTURNED BEDDING
STRIKE OF VERTICAL BEDDING
STRIKE AND DIP OF CLEAVAGE
AXIAL TRACE OF OVERTURNED ANTICLINE, STRIKE AND DIP OF AXIAL SURFACE, TREND AND PLUNGE OF FOLD AXIS
FAULT WITH STRIKE-SLIP COMPONENT OF SLIP
SANDSTONE BEDS, HORTON BLUFF FORMATION
SHALE, HORTON BLUFF FORMATION
RECENT SEDIMENTS
0
5
10 m
414800
N
FOLDED CLEAVAGE STEREOPLOT
N = 7

Figure 3.27: Detail map of Horton Bluff strata displaying folded cleavage in Little Rainy Cove. Shale and sandstone beds containing paleosols show discontinuous cleavage defined by darker clay minerals. Fabrics appear locally developed in an overturned fold that plunges steeply to the southwest and is cross-cut by minor dextral faults. Bedding in the south limb appears upright and overturned in sectors, possibly due to fold interference or faulting. Poles to cleavage show a girdle distribution (dots in stereogram, lower left) after an axis plunging to the southwest (+ symbol).

3.6. Rainy Cove Area

The mapping area designated as Rainy Cove includes the coastal section and shoreline that extend 400 m northeast from Rainy Cove Brook (Fig. 3.28). In the north end of the area, the Horton Bluff Formation is in angular unconformable contact with the overlying Wolfville Formation, which was not mapped in detail. The quality of exposures is very good in the cliffs and in the immediate shore area. Younging directions were determined by way-up indicators (Fig. 3.29).

3.6.1. Structure

Fig. 3.28 shows the overall structure of the area. At this scale, two main downward-facing folds dominate the centre of the section, and an upright syncline has been mapped in the south portion. A third downward facing fold was interpreted in the north portion of the area. In general, sandstone layers fold display 1B or 1C geometry, whereas shale layers can be classified as Class 3 of Ramsay (1967). Most of the mapped faults show a reverse component of displacement. Fabrics are scarce and locally developed.

3.6.1.1. Folds

In the central portion of the area, a major synformal anticline (A in Fig. 3.28, Fig. 3.30 A, and Fig. 3.31) is circular to elliptical (Davis and Reynolds, 1996), downward-facing, tight, asymmetrical, and plunges moderately to the southwest. The north limb of the fold occupies 38 m of cliff section, measured to the axial trace of a

nearby antiformal syncline (B in Fig. 3.28 and Fig. 3.32). It consists of moderately-dipping, overturned, north-younging strata. The south limb of the fold extends at least 25 m and consists of moderately-dipping, south-younging strata. The axial surface strikes northwest-southeast and inclines moderately to the southwest.

In the central portion of the area, a major antiformal syncline (B in Fig. 3.28, Fig. 3.30 B, and Fig. 3.32) is circular to elliptical (Davis and Reynolds, 1996), downward-facing, tight, asymmetrical, and plunges moderately to the southwest. The north limb of this fold spans 110 m in the cliff section, displaying subvertical and south-younging strata. The south limb consists of 38 m of overturned section measured to the axial trace of the above-described synformal anticline. The axial surface strikes northwest-southeast and inclines moderately to the southwest.

In the north portion of Rainy Cove, another synformal anticline has been interpreted (C in Fig. 3.28, Fig. 3.30 C, and Fig. 3.32). The fold is open, chevron-shaped, symmetrical, and plunges moderately to the northwest. The north limb of the fold cannot be followed in the cliff section due to colluvium and the nearby unconformity with the Wolfville Formation. Nevertheless, based on intermittent exposures, it probably extends for 25 m in the cliff and consists of steeply inclined, north-younging strata. The south limb of the fold was mapped for 110 m in the cliff towards the axial trace of antiformal syncline B. It includes subvertical, south-younging bedding surfaces. The axial surface is upright and strikes northwest-southeast.

In the south portion of Rainy Cove, a major syncline has been observed (D in Fig. 3.28 and Fig. 3.31). This fold is asymmetric and shows two main zones of

curvature that define a general box shape. Two main axial surfaces and hinges were constrained from cliff measurements. The north portion of the fold plunges moderately to the northeast and contains an axial surface that strikes northeast-southwest and dips moderately to the southeast (D1 in Fig. 3.28 and Fig. 3.31). The south portion of the fold plunges moderately to the northeast and displays an axial surface that strikes east-west and dips gently to the north (D2 in Fig. 3.28 and Fig. 3.31). Fig. 3.28 shows a third axial trace obtained as a result of the intersection of the main traces (D). This axial surface strikes northeast-southwest and dips moderately to the northwest.

The north limb of syncline D consists of beds that incline gently to the northeast and are south-younging. The north limb occupies 50 m of cliff section and is interrupted by a fault at the north end. Minor antiformal duplexes were observed in the north limb of the fold (Fig. 3.33 A). The south limb is represented by 20 m of steeply inclined strata in cliff section and is interrupted by a subvertical fault in the south end (Fig. 3.31).

In the cliff interval between syncline D and synformal anticline A, a conspicuous anticline was observed (E in Fig. 3.28 and Fig. 3.31, Fig. 3.33 B). The fold is tight, asymmetric, and subhorizontal. The anticline inner core is box-shaped, although the general shape of the fold is elliptical (Davis and Reynolds, 1996). The axial plane strikes northeast-southwest and inclines gently to the northwest. The north limb can be followed in the cliff for 25 m to the axial trace of synformal anticline A, displaying in upright bedding that strikes northeast-southwest and dips moderately to the southeast. The south limb is interrupted by a fault (Fig. 3.31) and

is overturned, striking northeast-southwest and dipping steeply to the northwest. The south limb displays a number of small-scale folds that have approximately the same orientation as the main anticline, with wavelengths ranging from 0.3 to 0.7 m.

In the beach, folded bedding surfaces with unclear facing direction were measured. Mean fold height and width for these folds are about 8 and 5 metres, respectively. Some of these folds are overturned and show similar orientations to the major downward-facing folds (Fig. 3.28).

In the north and south portions of the shore, outcrop-scale domes, where beds dip outward in all directions, were observed (Fig. 3.33 C). These structures are sometimes difficult to characterize due to their quality of exposure, but are possibly the result of fold interference (see Section 8.4).

In the north section of the cliff, three tight folds that plunge steeply to the northwest were observed. These folds display 0.5 m half-wavelengths. Access to these folds was difficult and no detailed measurements were obtained.

Bedding surfaces in Rainy Cove show a girdle distribution (Fig. 3.34-1) oriented northwest-southeast, dipping moderately to the northeast. The fold axes of major folds are in the southwest and northwest quadrants (Fig. 3.34-2). The girdle distribution of bedding indicates that regional folding occurs about a southwest-plunging axis. The axis is approximately coincident with the axis of downward-facing fold B (Fig. 3.34-1).

3.6.1.2. Faults

Most of the observed faults strike northeast-southwest and dip moderately to steeply towards the northwest and southeast (Fig. 3.28, Fig. 3.34-3). Most of the faults planes display slickenlines, defined by grooves and calcite fibres. Slickenlines indicate that a majority of faults are reverse. Offset of bedding ranges from 2 to 7 metres. Some fault planes did not exhibit any slip indicators and therefore are difficult to characterize kinematically.

High in the cliffs, some fault planes show changes in orientation that could be the result of gentle folding affecting the faults. Measurements were not taken due to access problems to these outcrops. In general, the distribution of poles to fault planes (Fig. 3.34-3) appears as a girdle oriented northwest-southeast, possibly indicating a regional fold axis that plunges to the southwest.

Joints in the Rainy Cove area occur in the upper section of domes (Section 3.6.1.1), displaying varied orientations (Fig. 3.28). It is possible that the joints represent release or uplift fractures in areas of fold interference.

3.6.1.3. Fabrics

Cleavage is not penetrative and was observed in only a few locations within this area. It is better developed in shale than in sandstone layers, although it affects both lithologies. In thick sandstone beds and paleosols, darker clayish domains alternate with lighter lithons. Cleavage planes strike northeast-southwest and dip

moderately to the northwest (Fig. 3.34-4). In general, cleavage surfaces do not show axial-planar relationships to the main structures (Fig. 3.34-2 and 4).

3.6.2. Discussion

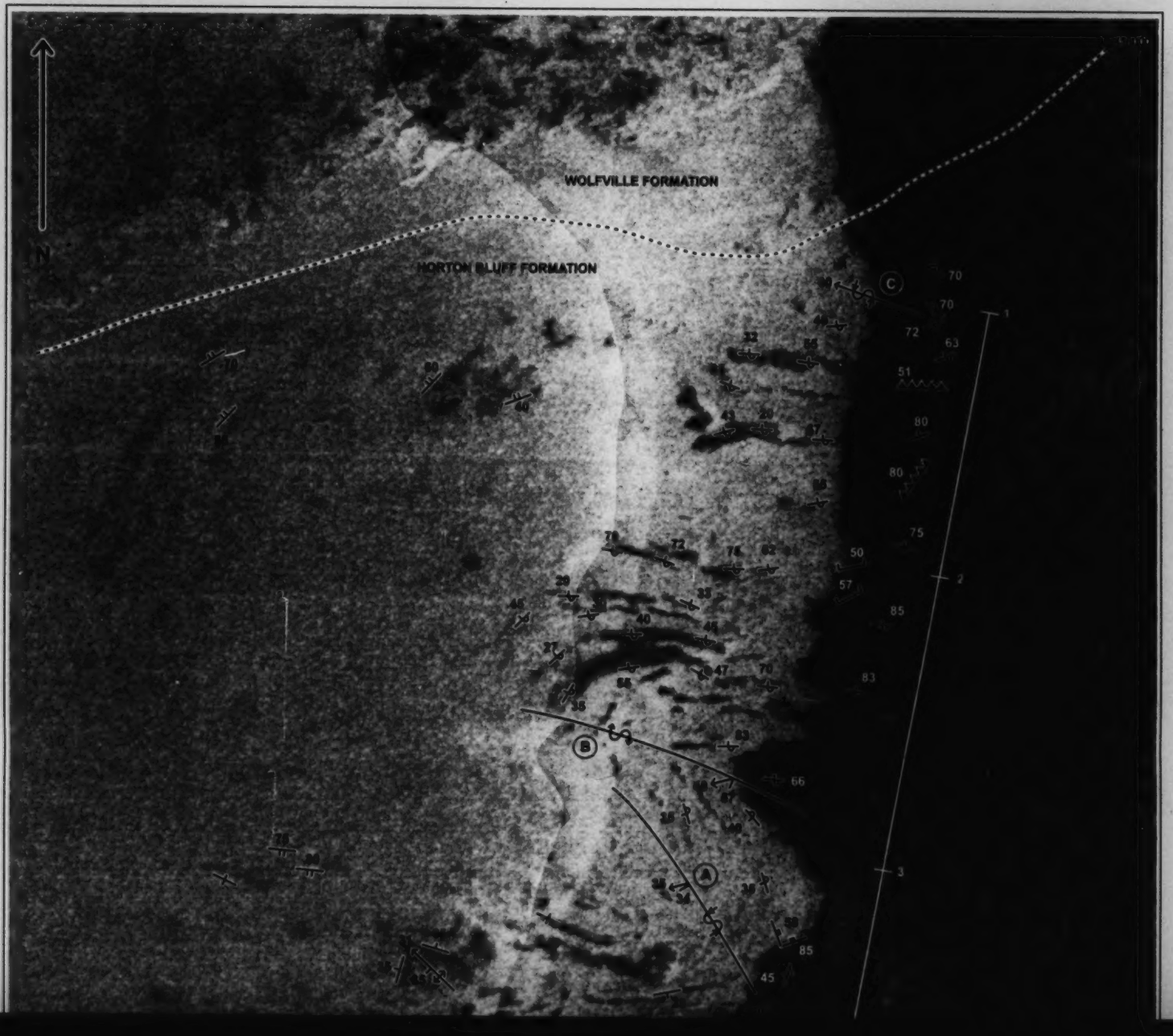
Folds documented in Rainy Cove display different orientations and scales. Field observations and interpretations about Rainy Cove make more sense when related to Little Rainy Cove (Section 3.5.1.1).

Tight folds with half-metre wavelengths observed in the cliffs are here designated F1 folds because of their similarities to the F1 folds observed in Little Rainy Cove, although this type of fold is less frequent in Rainy Cove.

The larger-scale folds are interpreted as F2 and F3 structures. In order to interpret the major folds of Rainy Cove, two alternative hypotheses are here presented (Fig. 3.35 and Fig. 3.36). The first hypothesis considers that folds A, B and C are F2 by refolded large-scale F3 folds. A large L3 hinge zone is proposed in the southwest part of the cliff profile to explain the attitude of bedding (see Fig. 3.35). The second hypothesis postulates that synformal anticline A is the only major F2 fold in the cliff, whereas folds B, C, and D would be F3 folds (Fig. 3.36). In both hypotheses, anticline E is interpreted as a parasitic and refolded F2. Overturned folds were observed in the beach about 100 m west from the cliff (Fig. 3.28) showing orientations comparable to anticline A. These overturned folds were also interpreted as strongly disharmonic, parasitic F2.

These hypotheses imply a Type 3 interference pattern (in the sense of Ramsay, 1967; Ramsay and Huber, 1983). In this pattern, L2 hinges of the refolded folds trend about the same direction as L3 hinges, whereas the axial planes of F2 are strongly refolded by F3 folds (Fig. 3.35, Fig. 3.36). This type of interference pattern is capable of producing downward-facing folds and was in fact observed in the nearby area of Walton (see Chapter 9). The domes mapped in the beach (see Section 8.3.1.) are also interpreted as being part of fold interference patterns, although the quality of exposures makes it difficult to assess which generations of folds (F1, F2, F3) are involved in these outcrops.

Fig. 3.34-1 shows poles to bedding in a girdle distribution, possibly dispersed in the southwest and northwest quadrants. In general, the bedding girdle distribution suggests a regional fold axis that plunges to the west or southwest, suggesting a northwest-southeast shortening (Fig. 3.34-1). The distribution of faults planes (Fig. 3.34-3) is consistent with this direction of shortening. Observations of some fault planes and the apparent girdle distribution shown by stereoplots of poles to faults suggest that the fault planes were folded about a regional axis that plunges to the southwest.


N
WOLFVILLE FORMATION
HORTON BLUFF FORMATION
A
B
C
1
2
3

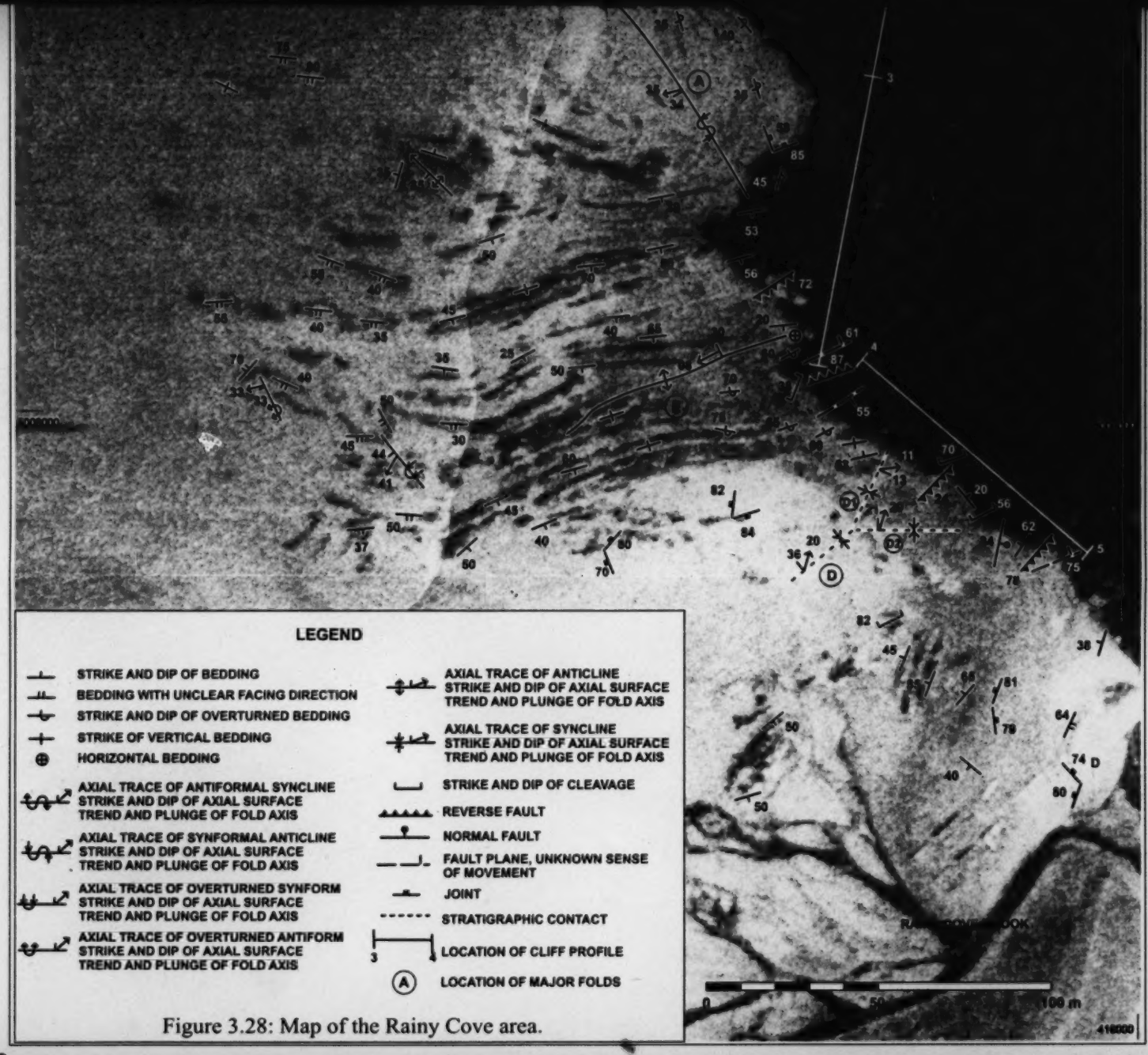

LEGEND
STRIKE AND DIP OF BEDDING
BEDDING WITH UNCLEAR FACING DIRECTION
STRIKE AND DIP OF OVERTURNED BEDDING
STRIKE OF VERTICAL BEDDING
HORIZONTAL BEDDING
AXIAL TRACE OF ANTIFORMAL SYNCLINE STRIKE AND DIP OF AXIAL SURFACE TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNFORMAL ANTICLINE STRIKE AND DIP OF AXIAL SURFACE TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF OVERTURNED SYNFORM STRIKE AND DIP OF AXIAL SURFACE TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF OVERTURNED ANTIFORM STRIKE AND DIP OF AXIAL SURFACE TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF ANTICLINE STRIKE AND DIP OF AXIAL SURFACE TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNCLINE STRIKE AND DIP OF AXIAL SURFACE TREND AND PLUNGE OF FOLD AXIS
STRIKE AND DIP OF CLEAVAGE
REVERSE FAULT
NORMAL FAULT
FAULT PLANE, UNKNOWN SENSE OF MOVEMENT
JOINT
STRATIGRAPHIC CONTACT
LOCATION OF CLIFF PROFILE
LOCATION OF MAJOR FOLDS
0
50
100 m

Figure 3.28: Map of the Rainy Cove area.

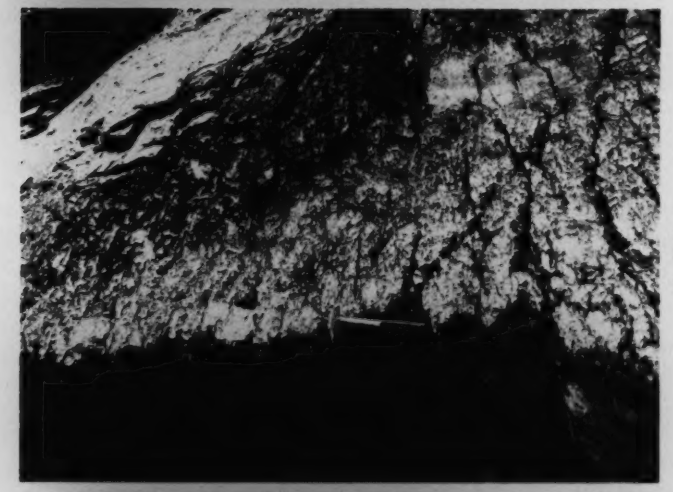


Figure 3.29: Sedimentary features in Horton Bluff strata, Rainy Cove area.

A) Groove and load casts in fine sandstone and shale (hammer for scale).

B) Paleosols containing mudcracks (hammer for scale).

C) Lycopsid fossil in sandstone bed (coin for scale).

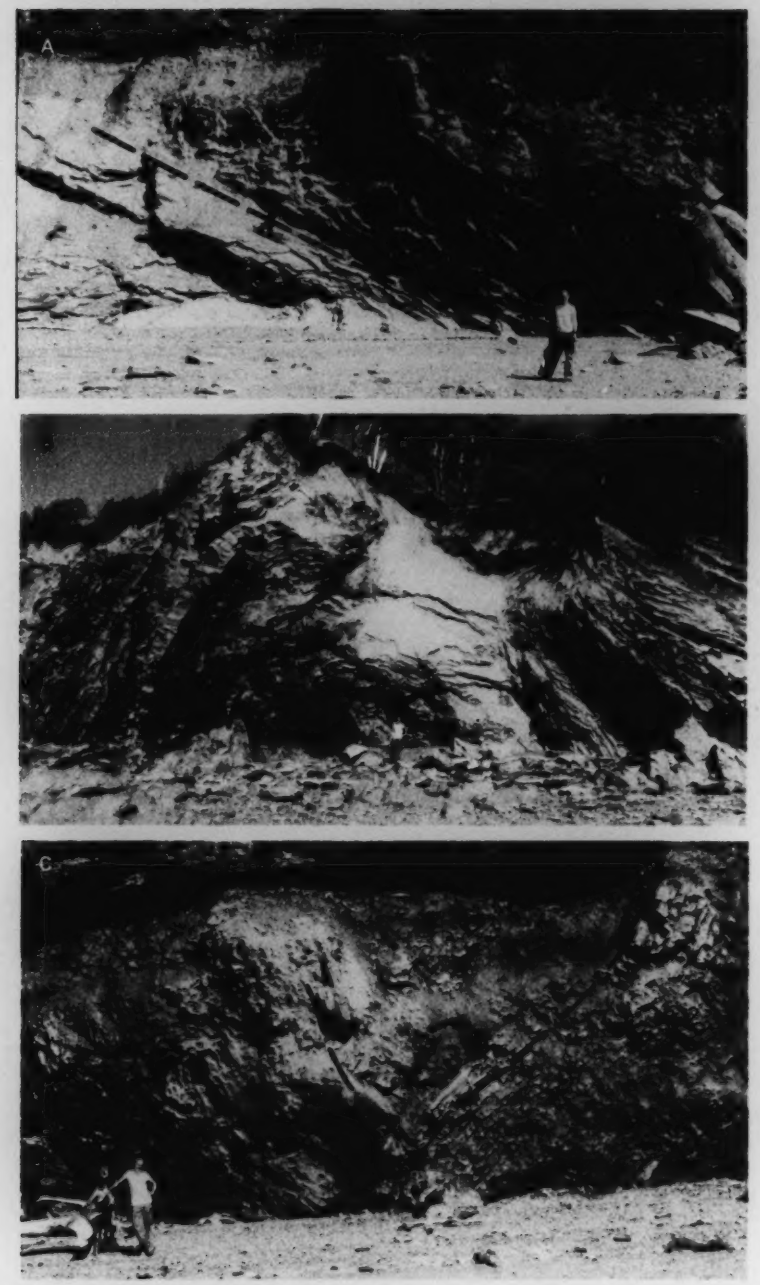


Figure 3.30: Downward-facing folds in cliff section, Rainy Cove area.
A) Major synformal anticline A (person for scale).
B) Major antiformal syncline B (person for scale).
C) Synformal anticline C (person for scale).

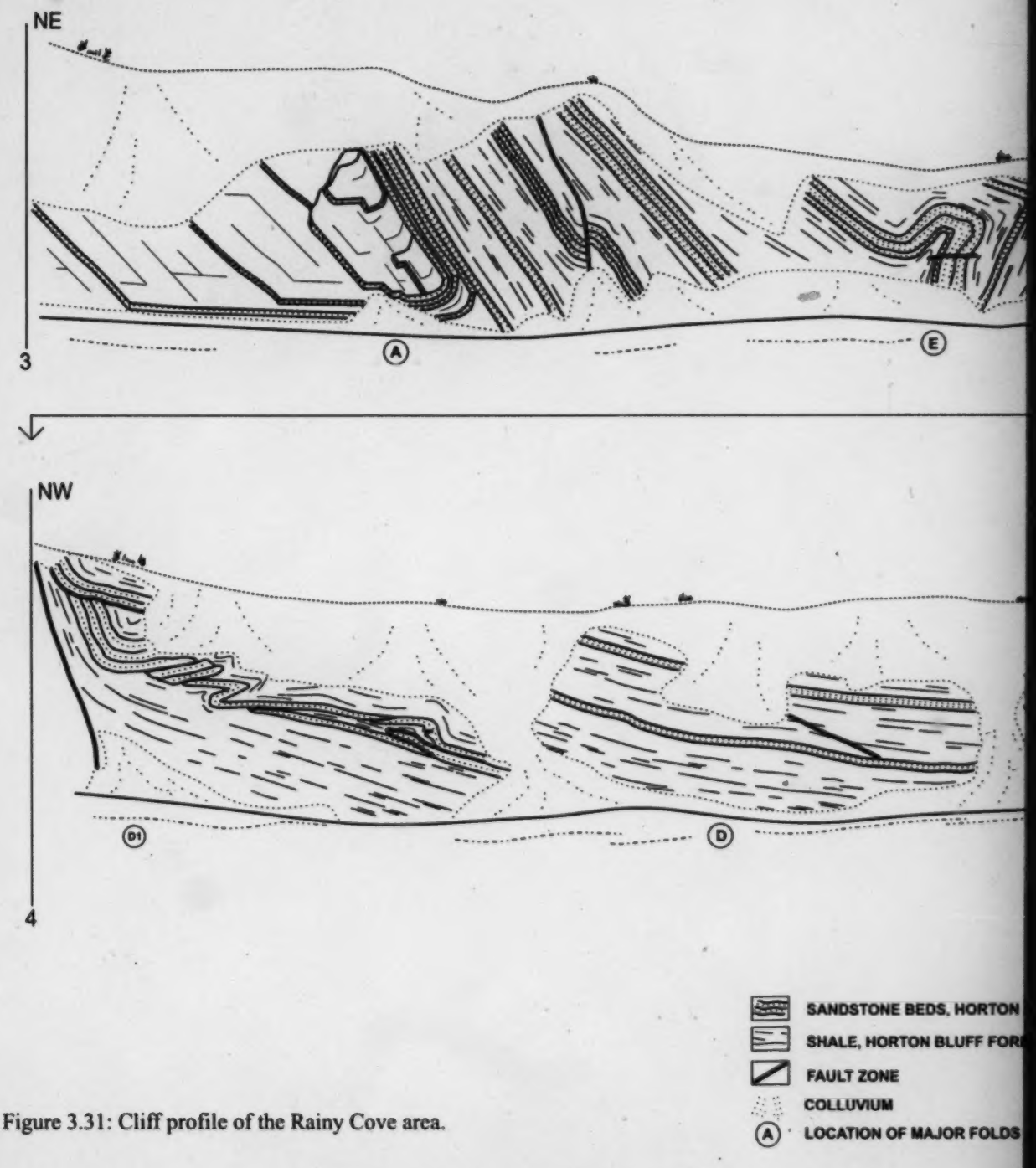
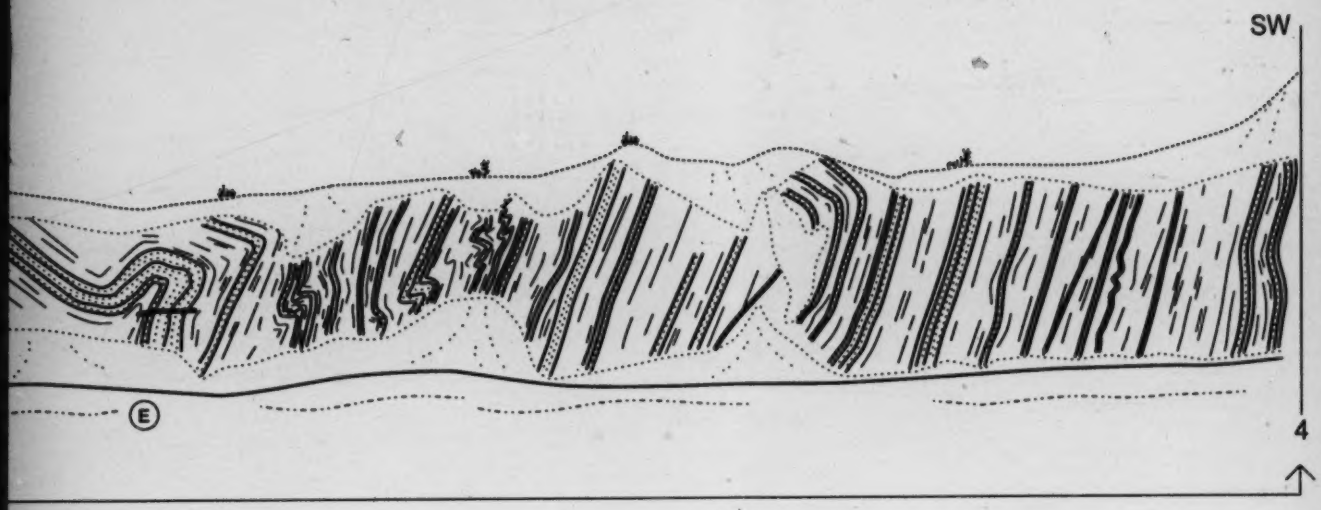
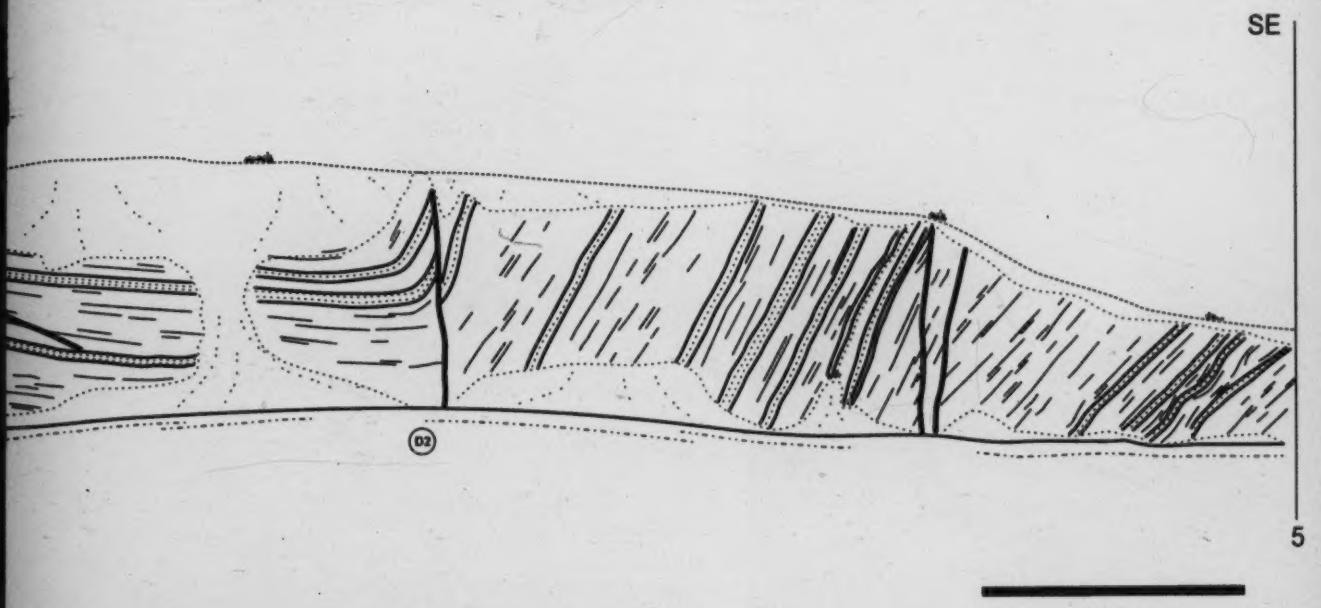


Figure 3.31: Cliff profile of the Rainy Cove area.





10 m

SANDSTONE BEDS, HORTON BLUFF FORMATION (HORTON GROUP)

SHALE, HORTON BLUFF FORMATION (HORTON GROUP)

FAULT ZONE

COLLUVIUM

LOCATION OF MAJOR FOLDS

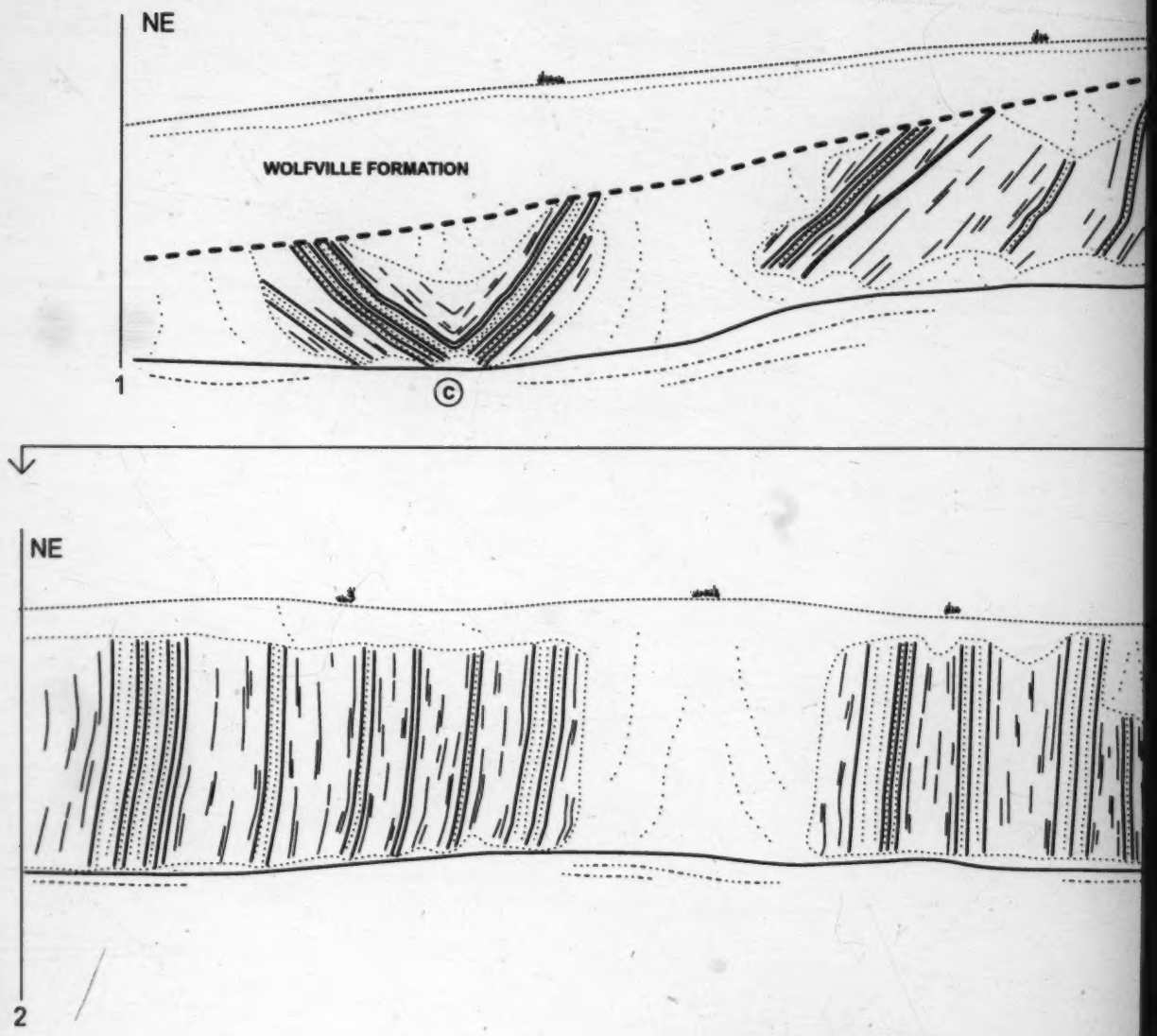
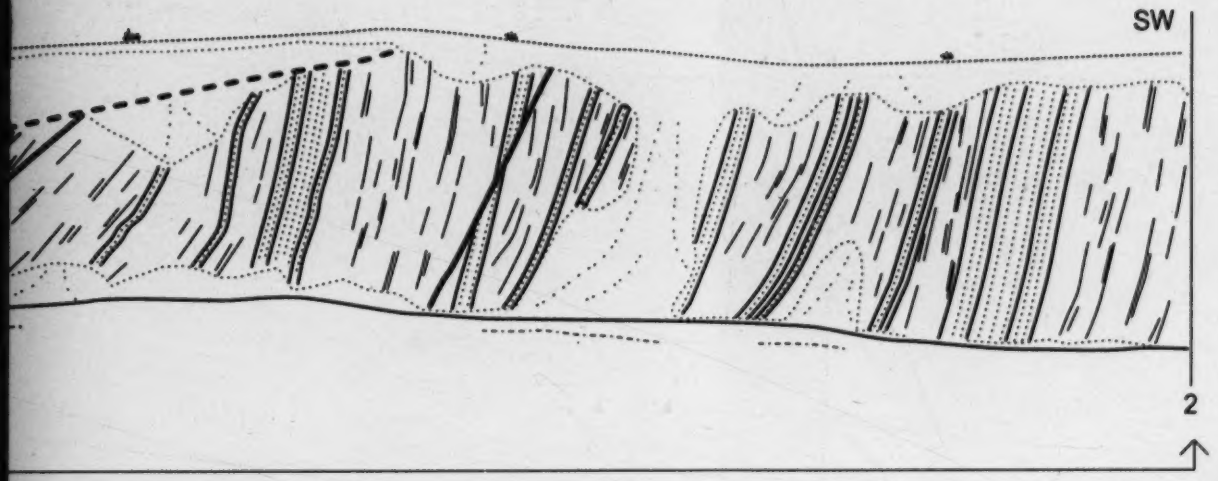
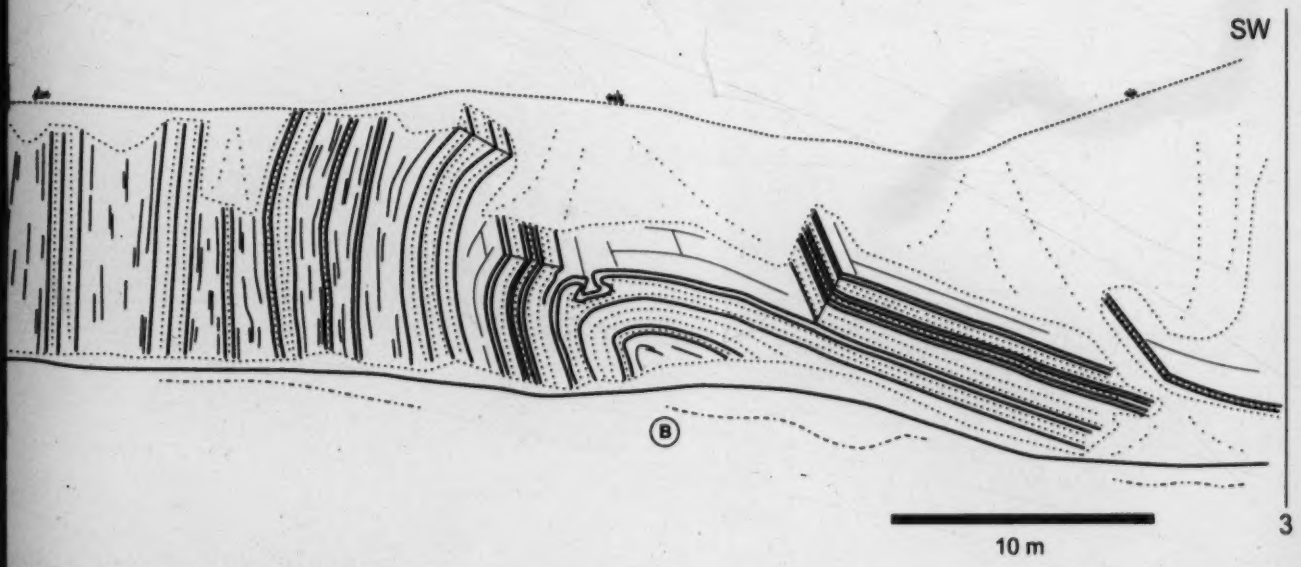


Figure 3.32: Cliff profile of the Rainy Cove area.





EDS, HORTON BLUFF FORMATION (HORTON GROUP)

ON BLUFF FORMATION (HORTON GROUP)

IC CONTACT

MAJOR FOLDS

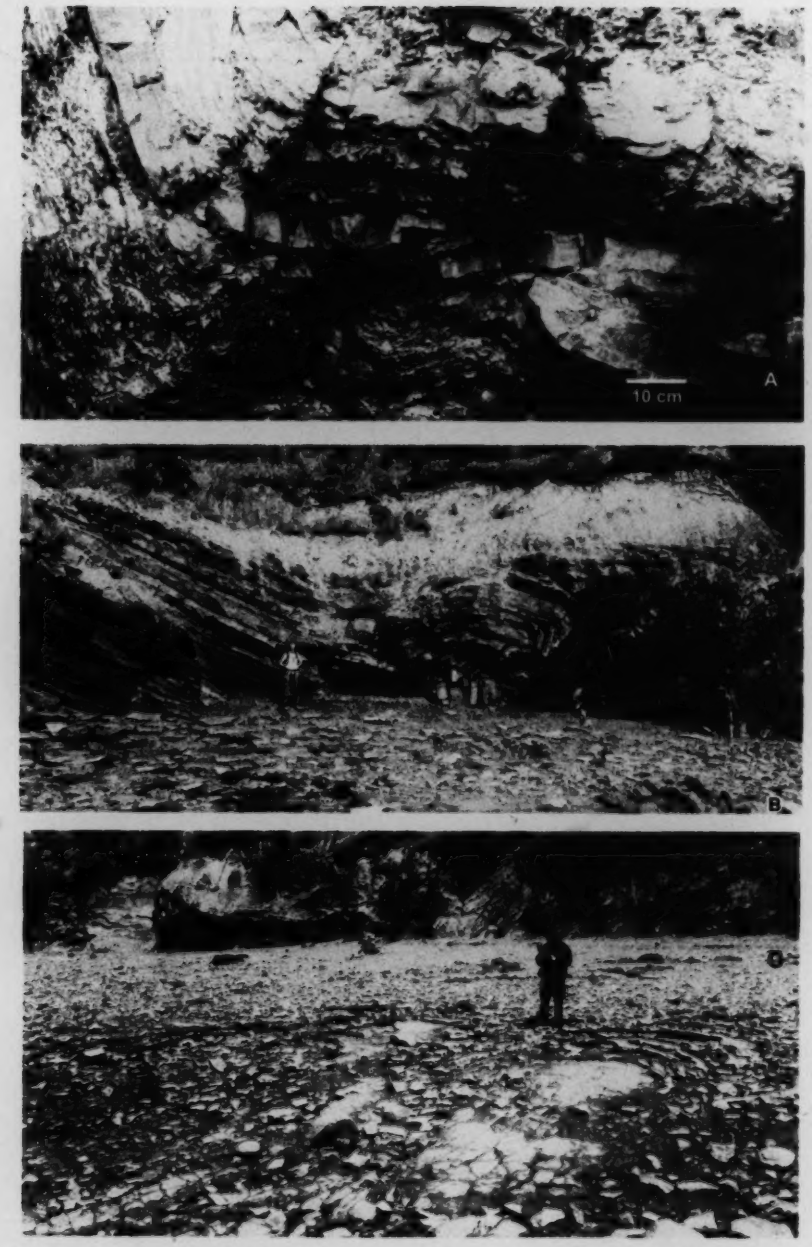


Figure 3.33: Upright folds and domes in Rainy Cove. A) North limb of major syncline D showing minor antiformal duplexes. B) Major anticline E as seen in cliff section (person for scale). C) Domes in the shore with beds dipping outward in all directions (person for scale).

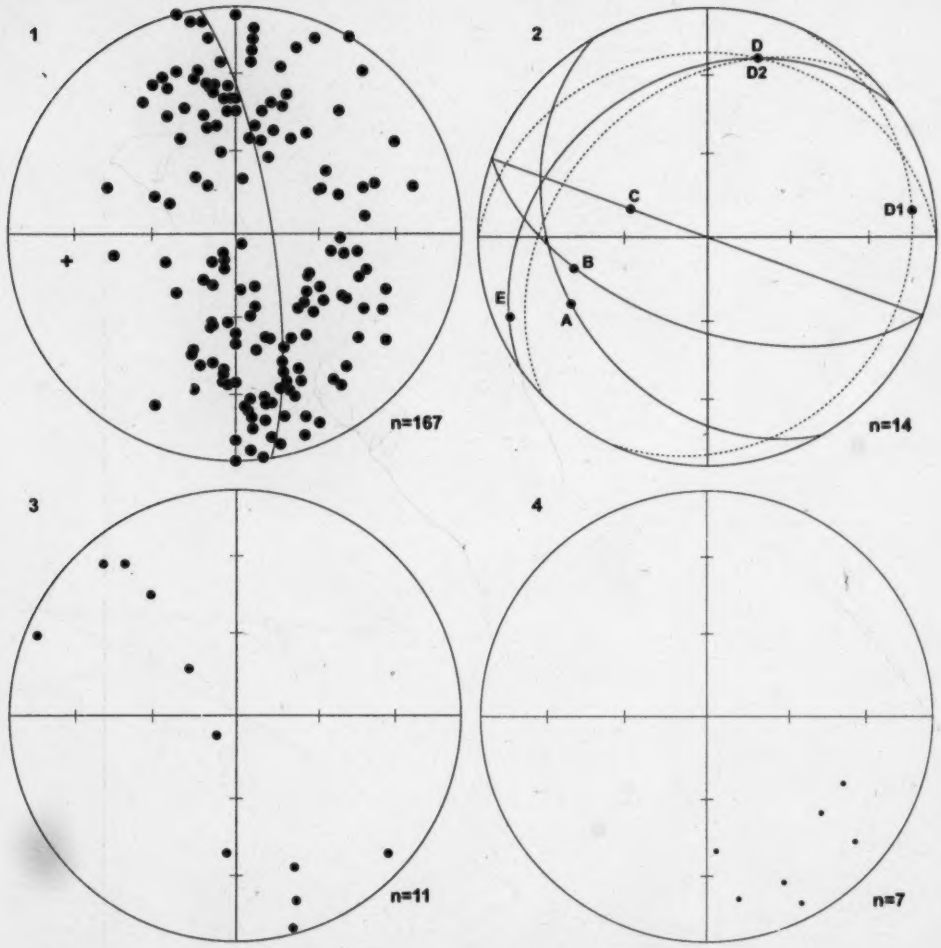


Figure 3.34: Stereographic projections, Rainy Cove area. 1) Poles to bedding (dots) show a girdle distribution (great circle), suggesting a regional fold axis that plunges to the west-southwest (+ symbol). The dispersion in the girdle is caused by measurements in the northwest and southwest quadrants. These measurements were obtained near domes. 2) Axial surfaces (great circles) and fold axes (dots) of major folds, labelled according to the text, map, and cliff profiles: A- major synformal anticline, B-major antiformal syncline, C-synformal anticline (north portion of the area) D-major syncline (axial traces of box fold in dashed lines) E- subhorizontal anticline. 3) Fault planes (great circles). 4) Poles to cleavage (dots).

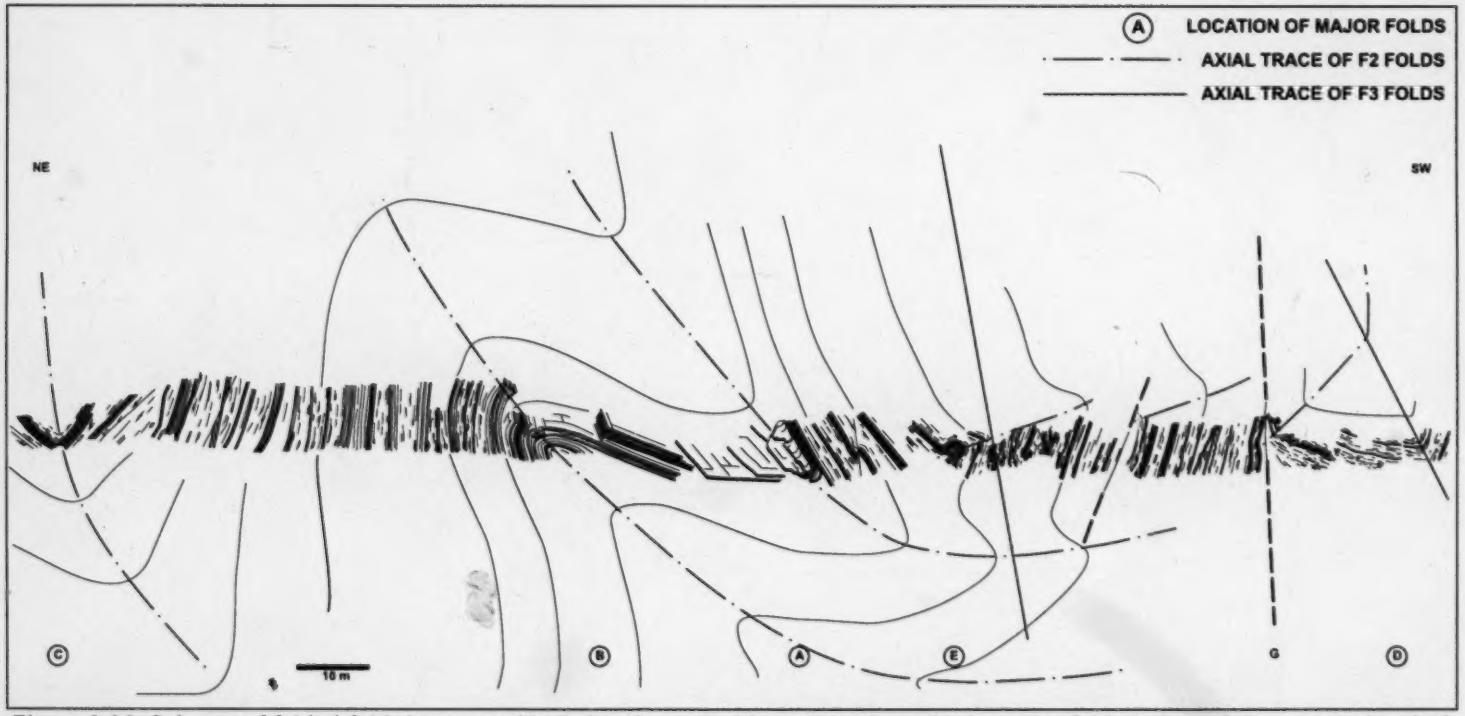


Figure 3.35: Scheme of folded folds interpreted in Rainy Cove. In this working hypothesis, major folds A, B, and C are considered F2 folds refolded by large-scale F3 folds. Anticline E would represent a parasitic F2, as other minor folds recorded in the cliff. This interpretation requires a large F3 hinge zone between fold E and fold D, affected by a major fault (G). The south limb curvature of box fold D is interpreted as a result of an F3 fold, whereas the north hinge zone would represent a folded F2.

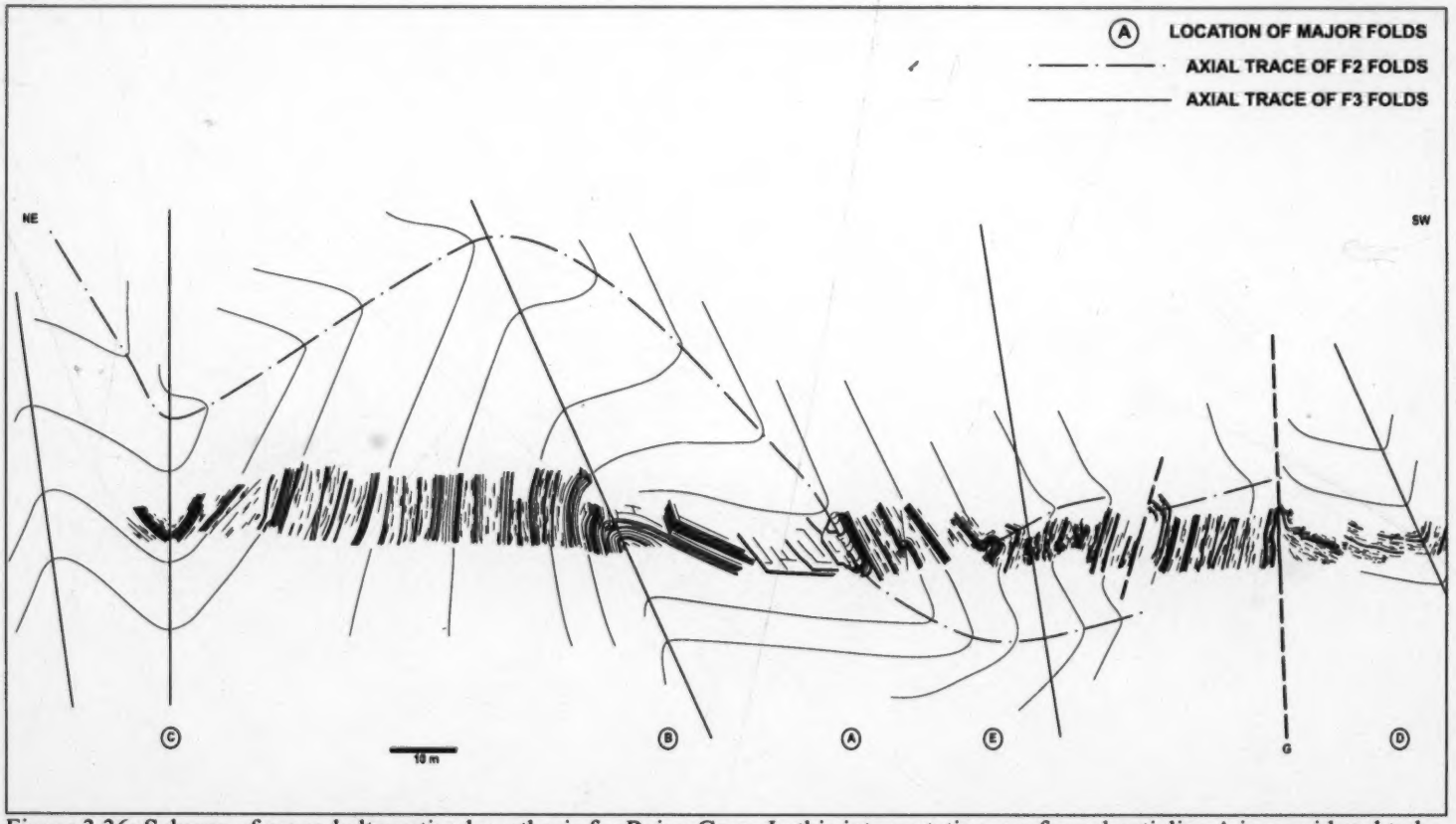


Figure 3.36: Scheme of second alternative hypothesis for Rainy Cove. In this interpretation, synformal anticline A is considered to be an F2 fold. As in Figure 3.35, anticline E represents a parasitic F2 fold and fault G is interpreted to be a major fault in the area. The other major folds are considered to be F3 folds.

3.7. Walton Area

The Walton area includes approximately 3 km of coast section, divided in halves by the mouth of the Walton River (Fig. 3.37). The mapped outcrops correspond to the Horton Bluff Formation, the Cheverie Formation, the Macumber Formation, and the Wolfville Formation. The contact between the Horton Bluff and the Macumber Formation was inferred to be tectonic. The Wolfville Formation, not mapped in detail, is in unconformable contact with all other units.

3.7.1. Structure

The Horton Bluff Formation appears strongly deformed in the cliffs and in the shore (Fig. 3.38 A). Folds display various scales and are the most conspicuous structures in the area. Few fractures were observed. No fabrics were documented in this area.

The Cheverie Formation is poorly exposed in the area and it was mapped as a homoclinal sequence with no fabrics. The Macumber Formation crops out between Horton Bluff and Cheverie rocks, in a position not expected for a normal stratigraphic succession.

3.7.1.1. Folds

Folds observed in the Walton area are tight, asymmetrical, elliptical to chevron-shaped, and plunge gently to the southwest. In sandstone layers, folded layers can be classified as 1C of Ramsay (1967), whereas Class 3 geometry is more

common in shale layers. Folds occur at variable scales. Minor folds display wavelengths in the order of 1 to 5 metres, are overturned, and plunge gently to the southwest. Minor folds display curviplanar axial surfaces that strike northeast-southwest and incline gently to steeply towards the northwest and southeast. These folds appear refolded by the major folds (Fig. 3.38 A and B, Fig. 3.39). Major folds were inferred and geometrically constrained in the area (Fig. 3.37). Axial surfaces of major folds strike northeast-southwest and are upright. Major fold wavelengths range from 60 to 100 m.

In the shore, a few small-scale folds with varied orientations were observed. These folds are elliptical (Davis and Reynolds, 1996), tight, double-plunging, and display wavelengths of about 0.5 metres. These folds are here called F1 folds because they show the same characteristics as the F1 folds mapped west of Walton (Sections 3.5 and 3.6).

Minor folds with curviplanar axial surfaces are here designated F2 because of their geometry and orientation, comparable to the F2 folds recorded in areas to the west (Sections 3.5 and 3.6). Major folds are therefore considered F3 folds, since they refold the F2 and are similar to the F3 folds interpreted in Rainy Cove (Section 3.6).

Poles to bedding surfaces display a girdle distribution (Fig. 3.40 A) that strikes northwest-southeast and dips moderately to steeply towards the northeast. The distribution of folded axial surfaces S2 suggests an L3 axis that plunges gently to the southwest (Fig. 3.40 B). The resulting interference pattern has to be one in which the first generation of fold hinges L2 remained unaltered, while the first generation of

fold axial surfaces S2 were folded. The interference pattern is interpreted in Subsection 3.7.2.

3.7.1.2. Faults

West of the Walton River, the quality of exposures made the recognition of fractures difficult. A thrust fault oriented northeast-southwest was recorded near the mouth of the Walton River, affecting Horton Bluff Formation.

In a small subarea east of the Walton River, the Horton Bluff Formation shows veins about 3 to 5 centimetres thick (Fig. 3.38 C). Veins are filled with calcite and quartz in aggregates. En echelon veins define a dextral shear zone oriented east-west, whereas other veins are subvertical and strike east-west (Fig. 3.38 C). Angles between the boundaries of the shear zone and en echelon veins are smaller than 45 degrees, indicating an important component of extension.

Near the mouth of the Whale Creek, the Macumber Formation and Pembroke Breccia are exposed as elongated outcrops, aligned east-west and northwest-southeast (Fig. 3.37). The Pembroke Breccia appears indurated. A major fault zone running east-west is proposed to explain the structural relationship among units.

3.7.2. Discussion

Two main generations of folds, F2 and F3, were interpreted in the Walton area. In the proposed scheme, F1 folds are seen at outcrop scale and are variably oriented. Refolding of F2 by F3 folds is invoked here to explain the spectacular

downward-facing structures at Rainy Cove and Walton, since Type 3 interference pattern produces downward facing folds. F2 and F3 folds typically plunge to the northeast or southwest, except where F2 folds are severely re-oriented by F3 folds. F3 folds plunge to southwest.

Field observations and data projection show a Type 3 interference pattern (Ramsay, 1967; Ramsay and Huber, 1983) in which the F3 folds plunge gently to the west-southwest. In Type 3 interference pattern, the L2 and L3 hinges display approximately the same orientation. S3 axial surfaces were calculated to strike northeast-southwest and dip steeply to the northwest (Fig. 3.40 B).

En echelon veins indicate that dextral shear occurred locally. En echelon veins display orientations consistent with a component of extension, suggesting a transtensional zone at outcrop-scale. The mapped large-scale folds probably developed in a dextral transpression setting. It is not known whether the fold generations (F1, F2, F3) represent distinct episodes in the development of the deformed zone or whether they were progressively developed during a continuous process of transpression.

The nature of the fault zone inferred in Whale Cove is uncertain. This structure is provisionally interpreted as a normal fault zone approximately perpendicular to the dominant northeast-southwest stretch in the area.

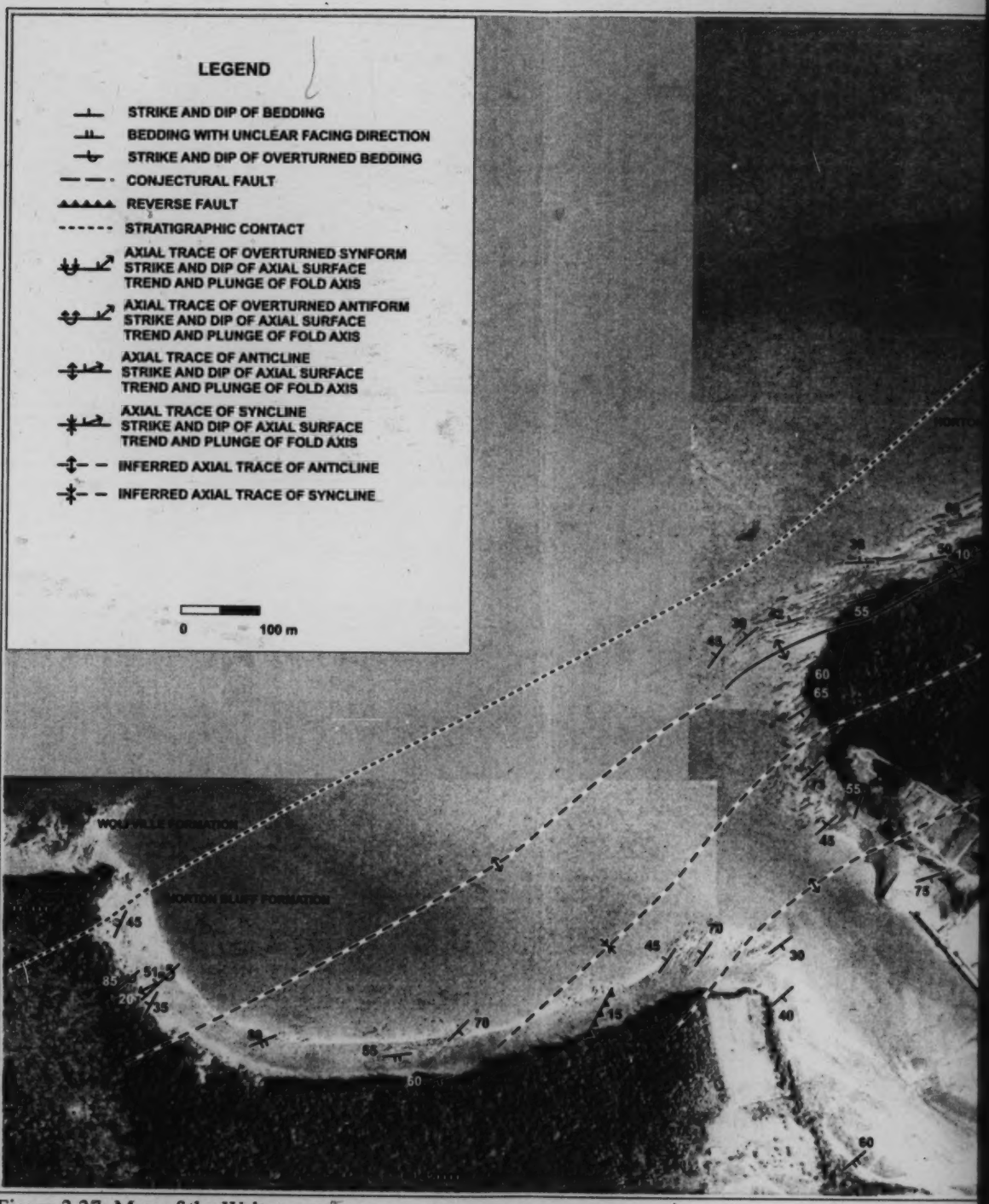

LEGEND
STRIKE AND DIP OF BEDDING
BEDDING WITH UNCLEAR FACING DIRECTION
STRIKE AND DIP OF OVERTURNED BEDDING
CONJECTURAL FAULT
REVERSE FAULT
STRATIGRAPHIC CONTACT
AXIAL TRACE OF OVERTURNED SYNFORM
STRIKE AND DIP OF AXIAL SURFACE
TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF OVERTURNED ANTIFORM
STRIKE AND DIP OF AXIAL SURFACE
TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF ANTICLINE
STRIKE AND DIP OF AXIAL SURFACE
TREND AND PLUNGE OF FOLD AXIS
AXIAL TRACE OF SYNCLINE
STRIKE AND DIP OF AXIAL SURFACE
TREND AND PLUNGE OF FOLD AXIS
INFERRED AXIAL TRACE OF ANTICLINE
INFERRED AXIAL TRACE OF SYNCLINE
0
100 m
WOLFVILLE FORMATION
HORTON BLUFF FORMATION

Figure 3.37: Map of the Walton area.

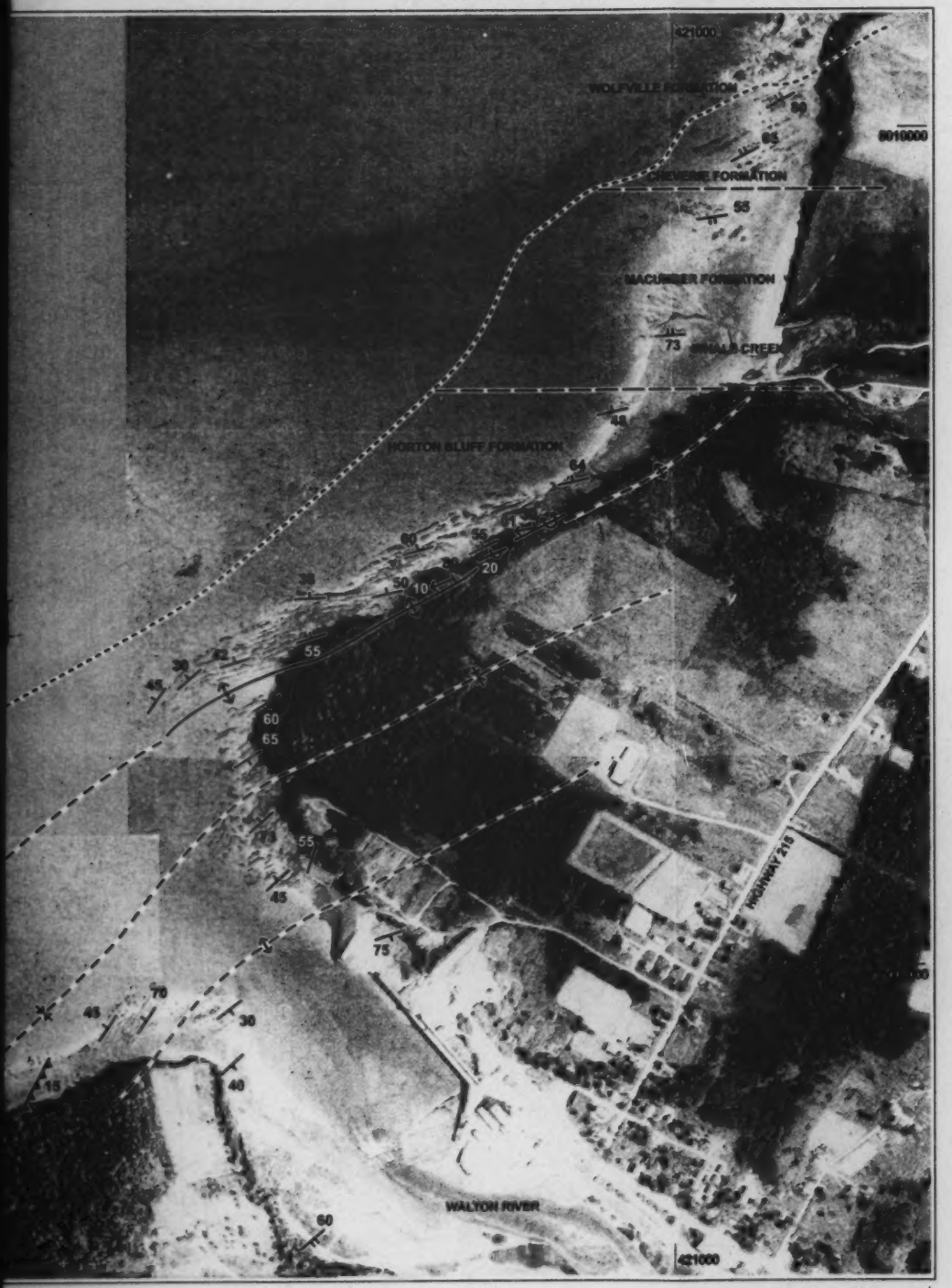
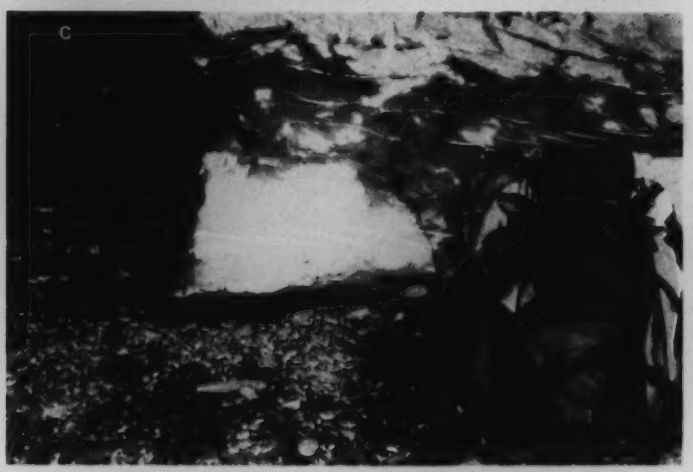

421000
WOLFVILLE FORMATION
65
8010000
CHEVERIE FORMATION
55
MACUMBER FORMATION
73
HORTON BLUFF FORMATION
64
60
55
30
20
10
55
45
60
65
55
45
75
70
45
30
15
40
60
HIGHWAY 215
WALTON RIVER
421000

Figure 3.38: Folded folds and shear zones in the Horton Bluff strata, Walton area.

A) Folded folds (designated F2) east of the Walton River. Folded axial traces highlighted (dashed lines).

B) F2 folds displaying curvilinear axial surfaces. These folds appear refolded by the major, inferred F3 folds (backpack for scale).



C) En echelon veins indicate that dextral shearing oriented east-west occurred locally (backpack for scale).

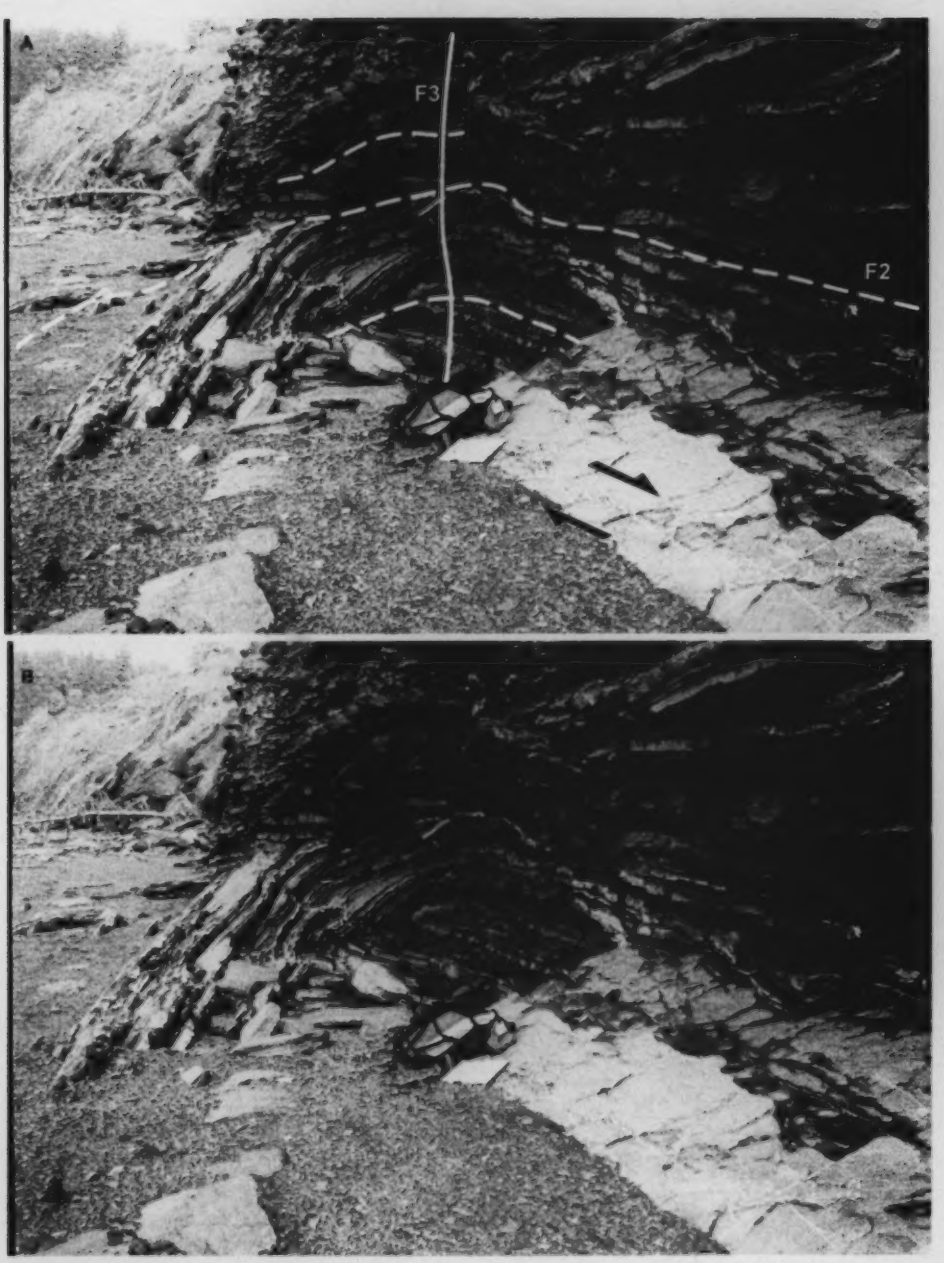


Figure 3.39: Type 3 interference pattern, as observed in the cliffs of Walton area. A) F2 and F3 fold traces appear in dashed and continuous lines, respectively. En echelon veins show a dextral shear zone oriented east-west (backpack for scale). B) Uninterpreted view of outcrop (backpack for scale).

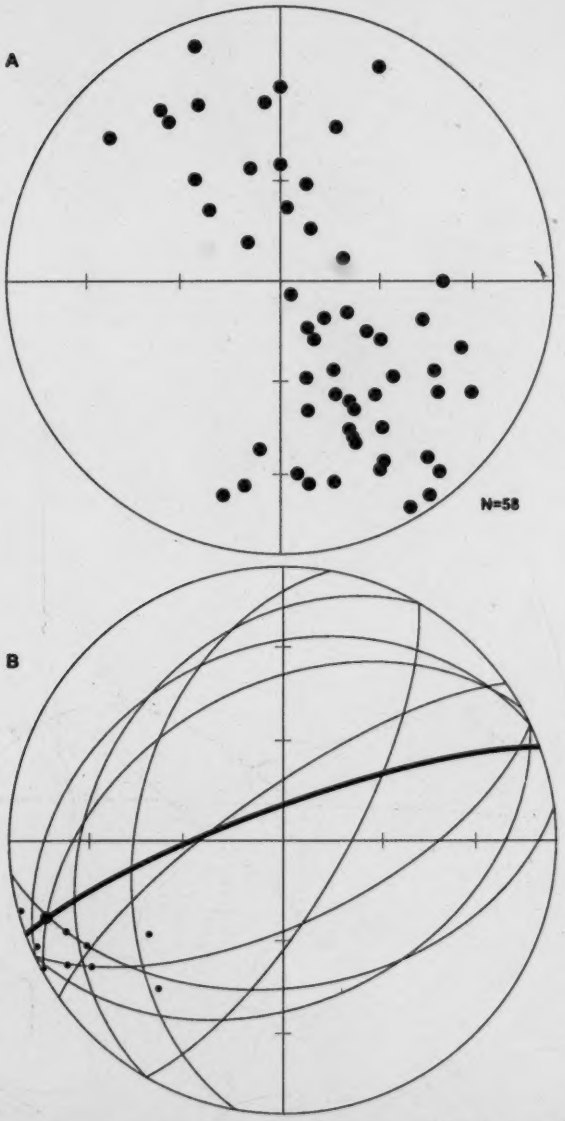


Figure 3.40: Stereographic projections, Walton area. A) Poles to bedding (dots) appear in a girdle that indicates a major fold axis plunging to the southwest. B) Fold axial surfaces (great circles) and fold hinges (dots). S2 axial surfaces strike northeast-southwest and dip to the southeast and northwest. L2 fold hinges plunge gently to the southwest. A mean S3 axial plane (bold line) was constructed using folded S2 surfaces. The mean S3 axial plane strikes northeast-southwest and dips steeply to the northwest. The mean L3 fold axis (larger dot) plunges gently to the southwest. In Type 3 interference pattern the L2 and L3 hinges display the approximately same orientation.

3.8. Eastern areas

Between Walton and the west bank of the Shubenacadie River (Fig. 3.41) Horton Bluff exposures occur near Tennycape, Minasville, Noel, and Lower Selma (Fig. 3.41). Elsewhere, Wolfville Formation unconformably overlies and obscures discontinuous Horton Bluff exposures. Subordinate outcrops of the White Quarry Formation are found in the banks of the Selma Brook and the coast near Selma (Fig. 3.41). Inland contacts between the Horton Group and the Windsor Group were compiled from previous works (Weeks, 1948; Crosby, 1962; Donohoe and Grantham, 1989; Moore et al., 2000).

In Tennycape, Minasville, and Noel areas, Horton Bluff Formation crops out as a homoclinal succession that generally strikes NE-SW and dips moderately SE (Fig. 3.41). In Lower Selma, the Horton Bluff Formation NE-SW and dips moderately (Fig. 3.41). No fabrics or structurally important fractures were observed. Weeks (1962) indicates that Horton Bluff strata is subhorizontal or dips gently SE in the south portion of Sterling Brook, East Noel River, and Selma Brook.

3.8.1. Discussion

The recorded changes in bedding orientation suggest the presence of large-scale folds (Fig. 3.41). Folds possibly plunge SW or NE. Considering their scale and orientation, these folds are comparable to the F3 folds mapped in Walton and Rainy Cove (Sections 3.6 and 3.7). The contacts between the Horton Bluff Formation and the White Quarry Formation near Old Quarry were interpreted as tectonic because of the abrupt changes in orientation.

3.9. Synthesis of field observations

Distinct structural changes are seen in progression from Summerville to Walton. The chaotic pattern of structures observed in Summerville is probably the result of drag zones produced by evaporite diapirs. Field relationships suggest overthrusting of the Horton Group in Cheverie and Summerville.

In Cheverie, Mutton Cove, Bass Creek, and Cambridge Cove areas, fold axial traces are oriented NE-SW and fold axes plunge to the southwest and northeast. Cleavage is axial planar. Most faults are reverse and strike NE-SW. Most of the recorded structures are consistent with a dextral transpression zone running east-northeast to west-southwest.

Structures recorded in Little Rainy Cove and Rainy Cove contrast in orientation with those mapped in the west. Fold axial traces strike NW-SE and fold axes plunge to the southwest. Some folds face downward. Cleavage was observed folded in some locations. Reverse and normal faults are variably oriented. In the Walton area, folds plunge SW and no fabrics were observed. Overprinting relationships are observed among the main folds, suggesting three generations of folds. Regional interpretation and discussion of structures are offered in Chapter 5.

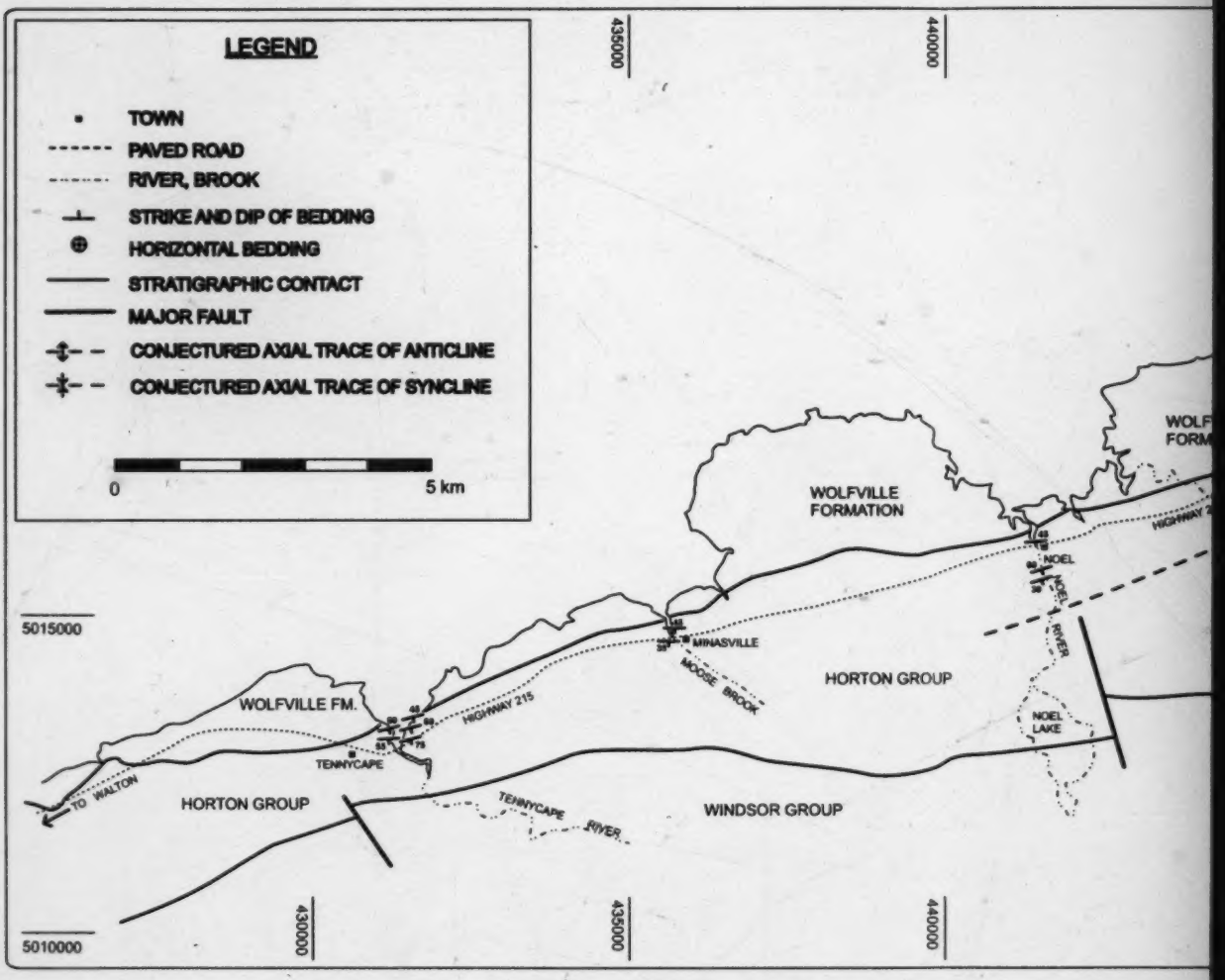
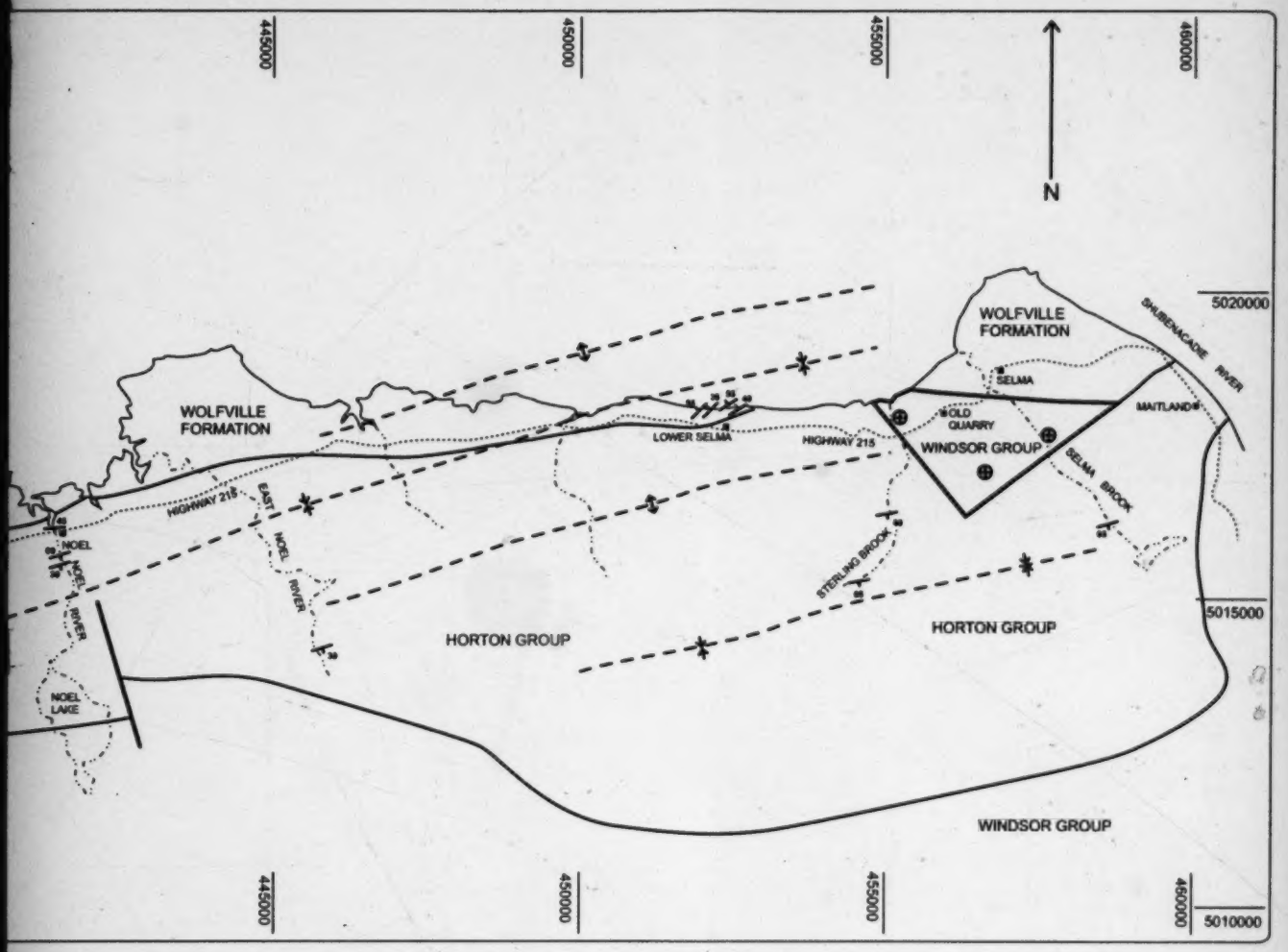


Figure 3.41: Map of Eastern Areas. These areas include Tennycape, Minasville, Noel, and Lower Selma. Cont
between Windsor and Horton strata were taken from Weeks (1948), Crosby (1962), Donohoe and Grantham (



d Lower Selma. Contacts between the Wolfville Formation and the Horton Group were recognized in the field. Contacts
hoe and Grantham (1989), and Moore et al. (2000).

4. Subsurface data

4.1. Introduction

The area of study has been subject of several drilling campaigns. After the discovery of the Walton Mine deposit in 1940, private companies drilled and surface-sampled properties near the coast between Walton and Summerville (Fig. 4.1). The Walton Mine was the world largest producer of barite for more than twenty years. The property was demonstrated to have base-metals and gold, produced in sulphide concentrates from 1965 to 1978, when the mine was closed. Some exploratory campaigns continued until 1989. Exploration consisted mainly of geophysical surveys followed by diamond drilling.

Some of the drill holes intersect the contact between the Horton Group and the Windsor Group. Forty-nine drill holes from the Stellarton Core Library database were studied. Drill holes in the study area range from 28 to 671 metres of depth. In some cases, the core was relogged in this study to verify the interpreted geology.

The areas of interest have been designated Walton Mine, Tennycape, Summerville, Stanley, and Cheverie (Fig. 4.1). The first three areas contain data from mining companies. The Stanley area was drilled in 1993 by the Nova Scotia Department of Natural Resources to determine the stratigraphy of poorly exposed Carboniferous rock units (Boehner and Edgecombe, 1993). The Cheverie area contains data from well Cheverie-01, drilled by Devon Canada Corporation in 2001.

Seismic lines were run by Devon Canada Corporation in 2000, covering the inland portion of the study area. These data were made available recently thanks to

permission from Devon Canada Corporation and are presented here to enable a broader interpretation of the subsurface.

4.2 Walton Mine area

The Walton Mine area (Fig. 4.1, Fig. 4.2) includes the Walton Mine Open Pit and all drill holes along the Horton-Windsor contact, up to 3 km southward from the pit, which includes the Sturgis Mine and the Lantz Mine, manganese prospects in the area to the southwest.

During the sixties, Cuvier Mines drilled the ST and WS drill hole series, and Macobar drilled the S66, S67, and S68. In 1988, Gunnar Gold explored the same zone with the S88 series. All these drill holes failed in finding deposits of commercial proportions. However, they offer valuable subsurface information for this study.

4.2.1 Stratigraphy

The characteristics of the stratigraphic units in the Walton Mine area are described by O'Sullivan and Macfie (1988). The Horton Group appears as a succession of reddish grey, well indurated, finely laminated fine sandstone, interbedded with dark grey to dark brown shales. Some intervals show gradation from fine sandstone to shale, whereas other intervals display more abrupt textural changes. Calcareous sandstone intervals were occasionally reported in the S66-68 core series. The colour, rock-type, texture and stratigraphic succession described in

the logs strongly suggest that these rocks are part of the Cheverie Formation. However, since dark grey fine sandstones interbedded with medium grain-sized sandstone layers of quartzitic composition were also described in the logs, some intervals may correspond to the Upper Member of the Horton Bluff Formation.

The base of the Windsor Group consists of fine-grained, light grey limestone interbedded with red to brown calcareous shales. Alterations include oxidation and sideritization. Manganese nodules and barite are reported within the base of the Windsor Group. Dark grey to black limestone beds are reported to be due to microcrystalline sulphide mineralization. Multiple breccia horizons have been reported stratigraphically above the limestone (O'Sullivan and Macfie, 1988; Hudgins, 1984). These intervals are characterized by the presence of grey limestone clasts, 2 to 5 centimetres in diameter, in a yellow grey calcareous matrix, and strong changes in thicknesses. Many drill holes did not find this interval. The limestone unit described at the base of the Windsor Group is interpreted here as the Macumber Formation. The breccia intervals logged in several drill holes are comparable to the Pembroke Breccia.

Grey-banded anhydrite with occasional fine layers of dark grey limestone overlie the above-mentioned units. In general, these have been avoided by prospectors and are therefore absent in the studied core. The only exceptions are some anhydrite and gypsum layers reported in the S88 series (O'Sullivan and Macfie, 1988). The anhydrite-gypsum intervals are considered here as part of the White Quarry Formation.

4.2.2. Structure

The dominant feature of the Walton deposit is a prominent northwest-southeast fault zone that dips steeply to the north (O'Sullivan and Macfie, 1988), exposed in the Walton Mine Open Pit (Fig. 4.2). Based on rock exposures in the pit and the mine shafts, this fault has been interpreted as strike-slip by O'Sullivan and Macfie (1988).

Outcrops are scarce and not enough to postulate deformation geometries. The interpreted top and bottom picks of units in the drill hole logs suggest that the dominant feature in the Walton Mine area is a recumbent, tight fold, which plunges moderately to the southwest (Fig. 4.3, Fig. 4.4). Fold half-wavelength is about 200 m. The axial surface is subhorizontal or dips gently to the southwest. This large-scale fold resembles in style (but not in scale) the overturned F2 folds of Little Rainy Cove and Walton (see Sections 3.6 and 3.7).

In several drill holes, the Horton Group is intersected twice, reappearing at the bottom (see Sections B-B' and D-D' in Fig. 4.3). The above-mentioned fold resembles a nappe transported from the northwest. However, it is also possible that a combination of brittle and ductile structures (e.g., thrust faults and recumbent folds) could explain the stratigraphic repetition in the Walton Mine area. Due to the lack of detailed way-up information from the surface and from logged core, it is not possible to establish a limit between ductile and brittle deformation in the area. Regardless of which mechanism is accepted, the dominant structure requires a transport of the Horton Group above the Windsor Group.

4.3. Tennycape area

The Tennycape area is located one kilometre south of the Tennycape village (Fig. 4.1). Access is via secondary roads extending south from Highway 215. Metal Mining Corporation drilled two diamond drill holes in 1994, MB-07 and MB-08 (Fig. 4.1). The objective was to intersect the down-dip extension of highly altered limestone of the Macumber Formation (Black, 1995). The drilling program was not successful in outlining any mineralization of interest.

The Windsor Group is logged as a succession of reddish yellow to light grey, matrix-supported breccia, with angular limestone clasts up to 5 cm in diameter, and a calcareous fine matrix (Black, 1995). Some gypsum veins appear occasionally, associated to green alunite alteration. Minor dark grey dolomite and finely laminated limestone appear in some intervals. The reported lithology of the Windsor Group is been interpreted here as the Pembroke Breccia. The thickness of this unit varies greatly from one drill hole to another (Fig. 4.5 A).

The Horton Group consists of grey to reddish grey fine sandstones, interbedded with black shales (Black, 1995). Lamination and possibly cross stratification have been observed. Fine conglomerate levels of quartzitic composition and a dark grey sandstone matrix are rarely reported. Limonitization and hematitic stains are the most common alterations (Black, 1995). The Horton Group described in the drill holes of the Tennycape area is interpreted here as containing the Upper Member of the Horton Bluff Formation and possibly the base of the Cheverie Formation. Drill hole MB-07 intersected the Horton Group at the surface and near the bottom (Fig. 4.5 A). A fault gouge zone is reported between the Horton Group at

the surface and the Windsor Group (Black, 1995). A thrust fault possibly explains the reported fault gouge zone and the transport of Horton Group on top of Windsor Group. Further interpretation remains open to possible combinations of ductile and brittle deformation structures, as in the Walton Mine area case. The direction and the attitude of transport of the fault cannot be deduced with only two drill holes.

4.4. Summerville area

The Summerville area includes outcrops between the Summerville village and Centre Burlington (Fig. 4.6). Maritimes Exploration drilled four diamond drill holes in 1945, closely located to Highway 215. Motivated by the discovery of barite in the Walton Mine, the aim of the drilling program was to explore the Macumber Formation. Only a few economic intervals were found.

The Windsor Group is described as a white to light grey gypsum with a constant thickness of 50 m, underlain by a brecciated limestone layer 20 m to 50 m thick (Curry, 1945; Brown, 1965). These two intervals correspond to the White Quarry Formation and the Macumber Formation/Pembroke Breccia, respectively. The Horton Group appears generally at the bottom of the drill holes in intervals of a few meters. It consists of finely laminated, dark grey to black, fine to medium sandstones, interbedded with black shales (Curry, 1945; Brown, 1965). These intervals probably correspond to the Upper Member of the Horton Bluff Formation.

Drill hole ME-4 encountered the Horton Bluff Formation at the surface. The Macumber Formation was intersected below a gouge zone, which was interpreted as

part of a thrust zone by Curry (1945). An interpreted drill hole cross section is offered in Fig. 4.5 B.

4.5. Stanley area

The Stanley area was drilled in 1993 by the Nova Scotia Department of Natural Resources to determine the stratigraphy of poorly exposed Carboniferous rock units, in support of ongoing geological mapping of the Kennetcook Basin (Boehner and Edgecombe, 1993). Drilling targets were established after the discovery of a negative gravity anomaly (Boehner, 1985). They included the Late Carboniferous Scotch Village Formation (Cumberland Group) and the Windsor Group. Drill hole STY93-1 (total depth: 305 m) intersected only the Scotch Village Formation, whereas drill holes STY93-2, STY93-3, and STY93-4 (total depths: 148, 166.5, and 181.5 metres respectively) were drilled through the Windsor Group only.

Core samples from drill hole STY93-1 were logged in the Stellarton Core Library facilities. The Scotch Village Formation in this particular hole consists of a succession of fine to medium, grey to yellowish grey sandstones with cross bedding and planar lamination, interbedded with grey brown to reddish brown shales (Fig. 4.7 A). Conglomerates were occasionally observed (Fig. 4.7 B). In general, sequences fine upward and exhibit plant debris and coal nodules (Fig. 4.7 C). Some medium-grained sandstone intervals are calcareous and contain rounded clasts of limestone. Pyrite and chalcopyrite are observed at depth in limestone and shales. The succession appears undeformed in the whole drill hole. Palynological samples from drill hole

STY93-1 were taken by Boehner (1994) at 79.6, 88.1, 102.8, 133.0, and 172.3 metres of depth. The age obtained was Westphalian.

The lithologies observed core samples and the apparently undeformed condition of the Scotch Village Formation are consistent with field observations made in the banks of the Kennetcook River (Section 3.1). The Scotch Village Formation has been mapped by Moore (1993b) in the Kennetcook River and the Stanley Area as an undisturbed clastic sequence, in presumed unconformable contact on much more highly deformed Horton and Winsdor strata.

The Windsor Group was described in the subsurface by Boehner and Edgecombe (1993) as a succession of dominant light grey to white gypsum interbedded with subordinate, unconsolidated reddish grey fine sandstone. Limestone levels were frequently reported. Drill holes STY93-2, STY93-3, and STY93-4 intersected the Lower Windsor Group, characterized by both clastic and evaporitic strata.

4.6. Cheverie area

Well Cheverie-01 (Fig. 4.1) was drilled by Devon Canada Corporation in 2001, reaching 1410 m of depth. The well was designed as a stratigraphic test, based on reports of petroliferous gypsum and limestone breccia from well 21H01D32E, drilled by Nova Scotia Oil and Gas Company in 1903, and well Coolbrook-01, drilled by Northstar Petroleum in 2001 (McDonald, 2001). Cutting logs from Well Cheverie-01 are available from 30 m to 1410 m. Electrical logs, including a sonic

log, were run from 1145 m to 1410 m. Core was obtained from 1243 m to 1350 m (McDonald, 2001). No significant petroliferous intervals were found.

The Horton Group, from 0 m to 404 m, is described as a succession of grey to reddish grey sandstones and shales. Sandstones are subordinate and quartzitic, with low to moderate porosity (McDonald, 2001). The Windsor Group, intersected from 404 m to 890 m, is dominated by grey calcareous shales and minor limestone in the upper section, grey anhydrite and white salt in the middle section, and light brown limestone in the lower section. The upper section had not been documented in wells 21H01D32E and Coolbrook-01 (McDonald, 2001). The Horton Group was intersected again, from 890 m to 1410 m, where it is described as red to grey, fine to coarse sandstones and shales. Sandstones are quartzitic in some subintervals, with one horizon that showed high porosity and indications of gas (McDonald, 2001).

Palynological examination of six samples from the interval from 0 to 404 m was carried out by Utting (2002b). A late Tournasian age was obtained, consistent with the age of the Cheverie Formation (Horton Group). The interval from 0 to 404 m has been interpreted as Scotch Village Formation by McDonald (2001), who also considers clastic units near the surface as Scotch Village Formation despite previous mapping of Horton Group (Weeks, 1948; Crosby, 1962; Stevenson, 1958; Boyle, 1957; Moore, 1993a; Moore, 1996; Moore and Ferguson, 1986; Moore, 1994; Ferguson, 1983; Johnston, 1999).

4.7. Seismic lines

Seismic lines run by Devon Canada Corporation in 2000 cover the greater part of the inland portion of the study area (Fig. 4.1). These data were originally processed and migrated into time by Devon Canada, later interpreted for this work using SeisWare 5.1 from Zokero, Inc.

Seismic lines WND00-001 to WND00-008 show a pair of strong reflections, R1 and R2, separating three zones, A, B, and C, with different seismic character (Fig. 4.8 to Fig. 4.14). Zone A, above the reflections, exhibits an irregular pattern in most sections. Negative seismic responses with discontinuous reflections are observed in Zone B, between R1 and R2. Zone C, below R1 and R2, displays less intense, more continuous, and regular reflections. A more discontinuous reflection, R3, is visible in the lower portion of most sections.

Seismic line WND00-001 crosscuts most of the north-south seismic lines (Fig. 4.1). Zone C appears thicker in the east part of the section. Seismic sections WND00-007 and WND00-008 show zone C thicker than in seismic lines in the west portion of the study area.

Reflection R1 is generally continuous and represents a negative seismic response (dark grey in Fig. 4.8 to Fig. 4.14). In the present work, reflection R1 was interpreted as the top of the Macumber Formation (Windsor Group). This interpretation is consistent with the anticipated acoustic impedance contrast at this boundary. The top of the Macumber Formation is thought to represent the passage from a gypsum-anhydrite interval (zone B, White Quarry Formation) to a limestone interval (zone C, Macumber Formation). In this passage, the acoustic impedance

based on common values for the lithologies involved (Sheriff, 1989), would decrease and the resulting reflection coefficient would be negative (Fig. 4.15).

The zone C shows a particular pattern of irregularities that can be compared to evaporitic sequences seen on most seismic sections (Jenyon, 1986). This pattern can be better seen in seismic section WND00-002 (Fig. 4.9), section WND00-003 (Fig. 4.10), and section WND00-004 (Fig. 4.11). Lateral changes observed in section WND00-004 from CDP 2742 to 3482, are here attributed to the presence of salt and shales in the Windsor Group (McDonald, 2001).

Reflection R2 is continuous and shows a negative seismic response (dark grey, seismic sections WND-001 to WND-008). This reflection is interpreted as the top of the Cheverie Formation (Horton Group). The change between a limestone (zone C, Macumber Formation) and a shale-sandstone interval (zone D, Horton Group) is predicted to produce a negative reflection coefficient.

Reflection R3 is discontinuous and shows a positive seismic response (white in seismic sections WND-001 to WND-008). It is interpreted as the passage from clastic Horton rocks to the basement unit (zone D, Meguma Group). Positive and negative reflections that overlie R3 probably represent basal conglomerates of the Horton Bluff Formation (Moore, 1986).

The seismic sections display curving and cross-cutting patterns that suggest complex structures. For example, reflectors shown in dashed line in section WND00-004 possibly correspond to the unconformity at the base of the Scotch Village Formation (Fig. 4.11). Abrupt discordances that appear as branched thrusts and

reverse faults are observed in section WND00-002 (Marked as pattern "2" in Fig. 4.9).

Cheverie-01 well was correlated with the seismic reflections of section WND00-002 (Fig. 4.9) by considering the logged lithologies, the corresponding seismic velocities, and the acoustic sonic log data of the well, which was only available for the lower section. Fig. 4.15 summarizes all calculations. The corresponding two-way time for the top of the Cheverie Formation in section WND00-002 is 490 milliseconds (Fig. 4.9). The mean seismic velocity obtained is 4069 m/s, a velocity consistent for an interval composed of gypsum, anhydrite, shales, and sandstones.

In line WND00-002 (Fig. 4.9), the base of the Horton Group was established based on a rapid downward change from regular to more irregular, diffuse reflectors near 180 milliseconds (two-way time). In the cutting log, the top of the Windsor Group is located at 404 m depth (McDonald, 2001), which is consistent with the two-way time displayed in the seismic section for an average velocity of 4069 m/s.

The lower part of the well (890-1410 m) was interpreted using the average differential travel time (215 microseconds/m) from the sonic log (1145 m - 1410 m). This parameter was used in the absence of other data to represent the entire Horton Group, since no significant lithological changes occur from 890 m to 1410 m. A calculated mean velocity for the logged interval of 4651 m/s is consistent with the lithologies found in the Horton Group (Fig. 4.15).

The surface geology (Fig. 4.1) can be compared with the present seismic interpretation. For instance, the Horton Group, which was interpreted in two

different intervals in section WND00-002 (Fig. 4.9), can be projected to the surface between common depth points (CDP) 2405 and 2771 (Fig. 4.9). In lines WND00-007 and WND00-008, the Horton Group was interpreted as a thick, continuous succession from the basement to the surface (Fig. 4.13, Fig. 4.14). Important discontinuities, possibly major faults, are observed in seismic section WND00-008 (Fig. 4.14).

The Horton Group displays a possible change in thickness suggested by line WND00-001 (Fig. 4.8). This change is also indicated by the contrast among lines WND00-002, WND00-003, WND00-007, and WND00-008 (Fig. 4.9, Fig. 4.10, Fig. 4.13, Fig. 4.14, respectively). Lateral changes in thickness of the Horton Group have been previously reported (Moore, 1986; Martel, 1990). This could be due to listric faults that affected the siliciclastic basement (the Meguma Group) and were active during the deposition of the Horton Group, producing a wedge-shaped profile of this clastic succession.

The Macumber Formation can be projected to the surface between CDP 3132 and 3315 of line WND00-001 (Fig. 4.8). The interpreted section WND00-007 (Fig. 4.13) shows the Macumber Formation projected to the surface near CDP 3181 (5 km south of Noel), roughly matching the regional map (Fig. 4.1). Seismic section WND00-006 (Fig. 4.12) does not display enough resolution to match the surface geology. Line WND00-008 (Fig. 4.14) displays two diffuse reflectors that could correspond to the Macumber Formation mapped south of CDP 4455 (Fig. 4.1).

The White Quarry Formation projects to surface between CDP 2954 and 3686 in line WND00-002 (Fig. 4.9, the resolution is poor from CDP 3686 to 4235)

consistently with the mapped surface geology (Fig. 4.1). Line WND00-003 (Fig. 4.10) shows shallow features between CDP 3896 and 4256 that may correspond to evaporites mapped in outcrop (Fig. 4.1).

The resolution of seismic sections WND00-007 and WND00-008 (Fig. 4.13, Fig. 4.14) decreases between 50-250 milliseconds, and therefore it is difficult to establish the subsurface occurrence of the Windsor Group mapped at the surface (Fig. 4.1).

4.8. Discussion

The Horton Group appears on top of the Windsor Group, according to the mining drill hole data for Walton Mine, Tennycape and Summerville areas (Section 4.2, 4.3, and 4.4). The interpreted seismic lines do not have good resolution at shallow depths, even at the level of the deepest mining drill hole (300-350 m). The interpretation of subsurface data (drill holes, well data, and seismic lines) indicates that the Horton Group is found in two different stratigraphic positions, completely different from what would be expected in an undisturbed succession. If the present interpretation for the subsurface and its relation with the surface geology is correct, then the Horton Group observed and mapped in coastal areas must be allochthonous, transported by a combination of relatively shallow recumbent folds and thrust faults at depth (Section 4.2.2 and 4.7).

Karstic and solution-collapse processes probably affected Macumber limestones in the area of study. Abrupt changes in thickness are shown in mining

drill holes from Walton Mine, Tennycape, and Summerville (Sections 4.1, 4.2, and 4.3). The distribution of the Pembroke Breccia at depth is described as erratic in several drilling reports (Curry, 1945; Brown, 1965; O'Sullivan and Macfie, 1988; Black, 1995). Abrupt discordances and curving patterns displayed in seismic sections are provisionally interpreted as cross-cutting and discordant relationships among layers of the Macumber Formation (Fig. 4.9, Fig. 4.11). In addition, Macumber limestones probably contain bioherms, which as primary features could have caused moderate changes in thickness (Boehner et al., 1989).

Mc Donald (2001) considers some units near the surface as Scotch Village Formation, inferring a regional unconformity at a depth of 404 m in Cheverie-01 well that separates Windsor evaporites from Cumberland clastics. Palynological analyses of samples from the upper part of well Cheverie-01 (Utting, 2002b; included here as Appendix I) and coast areas (Tennycape and Rainy Cove) demonstrate that units near the surface are correctly interpreted as Horton Group in this and previous works (Weeks, 1948; Crosby, 1962; Stevenson, 1958; Boyle, 1957; Moore, 1993a; Moore, 1996; Moore and Ferguson, 1986; Moore, 1994; Ferguson, 1983; Johnston, 1999).

The Scotch Village Formation has been studied by mining drill holes in the Stanley area. Some of the sections display broad reflections that are here attributed to the erosive base of the Scotch Village Formation (Fig. 4.8, Fig. 4.10, Fig. 4.11). Since the total thickness of the Scotch Village Formation has not been yet established (Boehner, 1994) the final interpretation remains open.

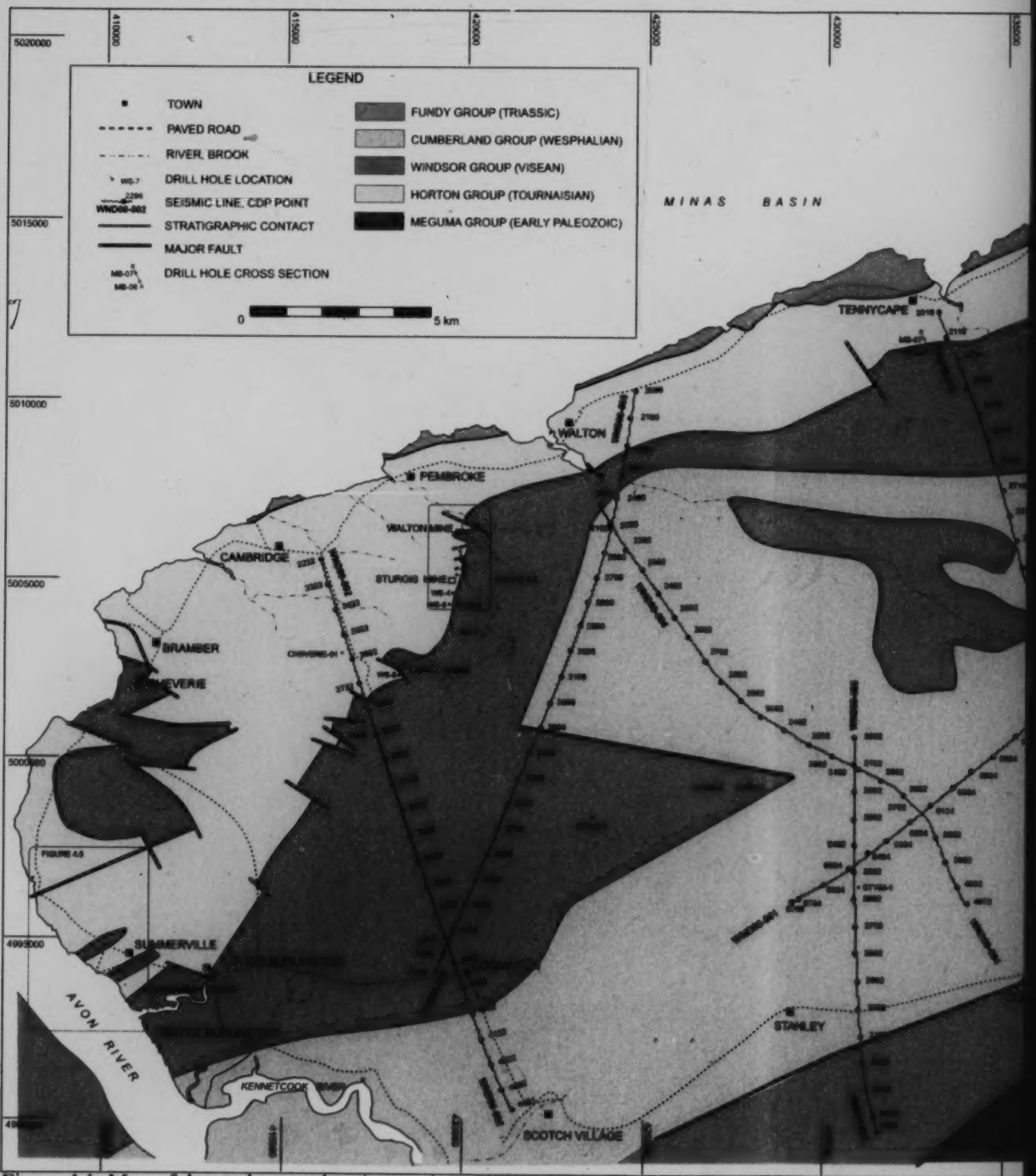
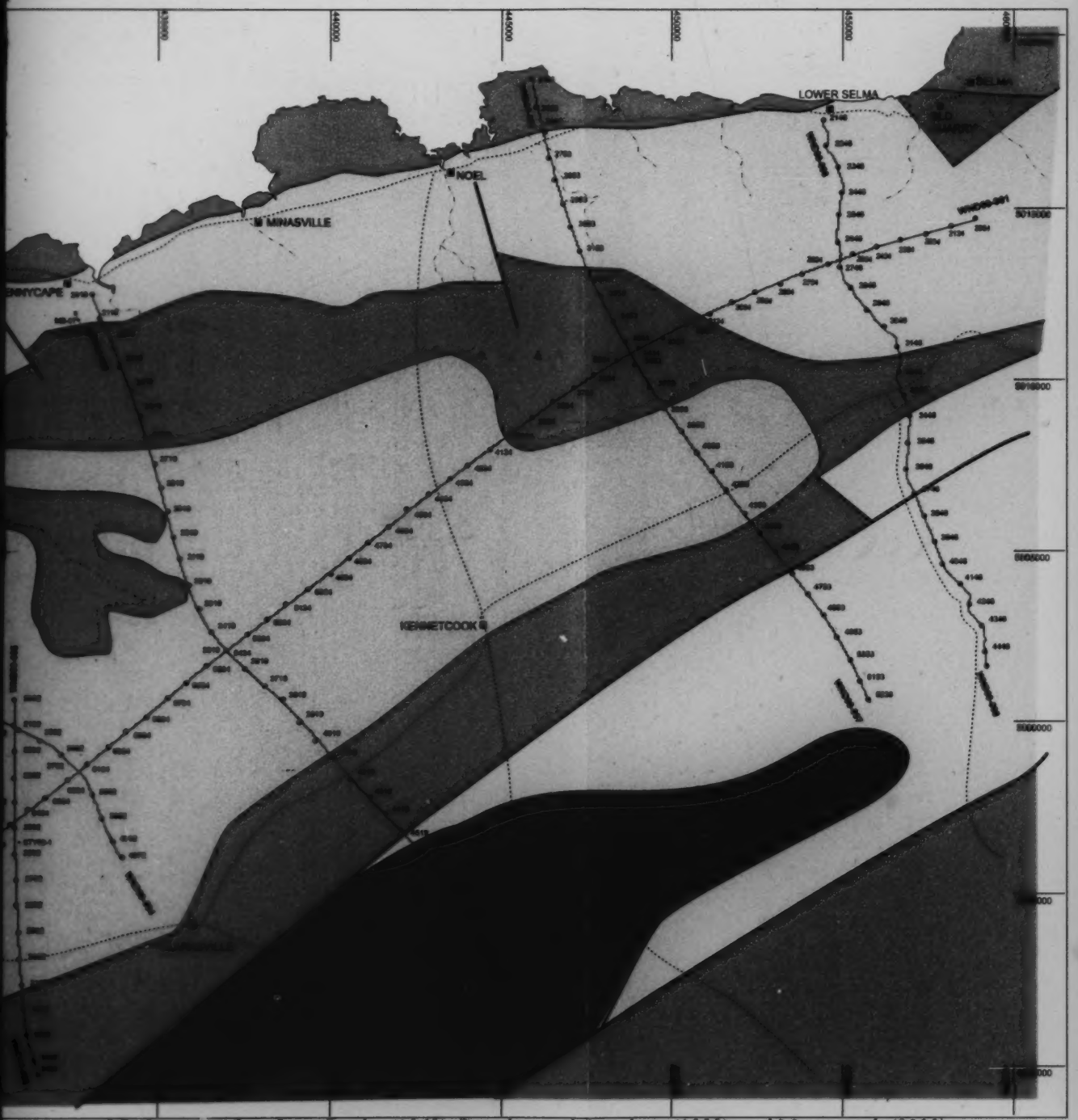
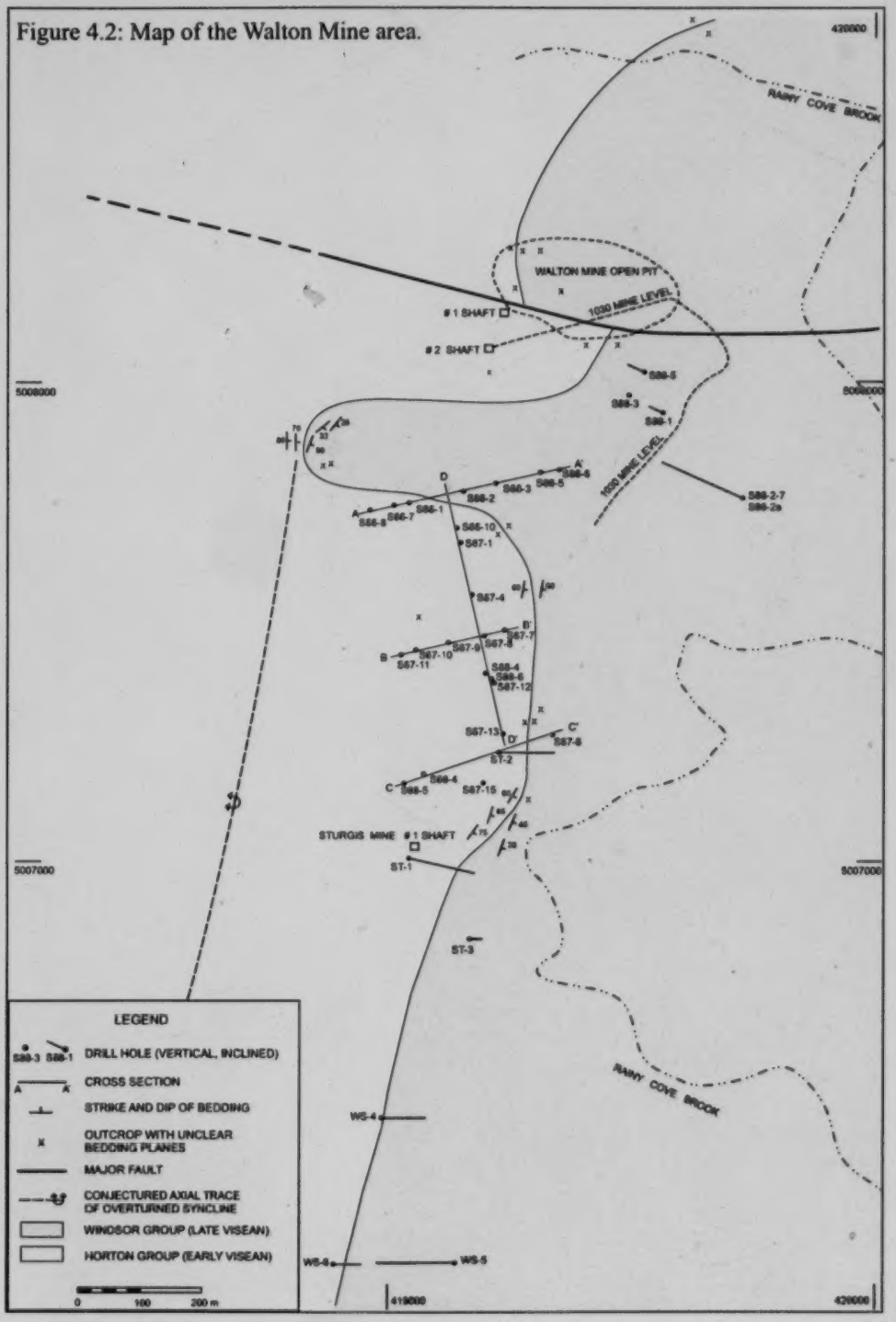


Figure 4.1: Map of the study area showing geology, drill holes, and seismic lines. Geologic contacts and faults



contacts and faults were taken from Crosby (1962), Donohoe and Grantham (1989), and Moore et al. (2000).

Figure 4.2: Map of the Walton Mine area.



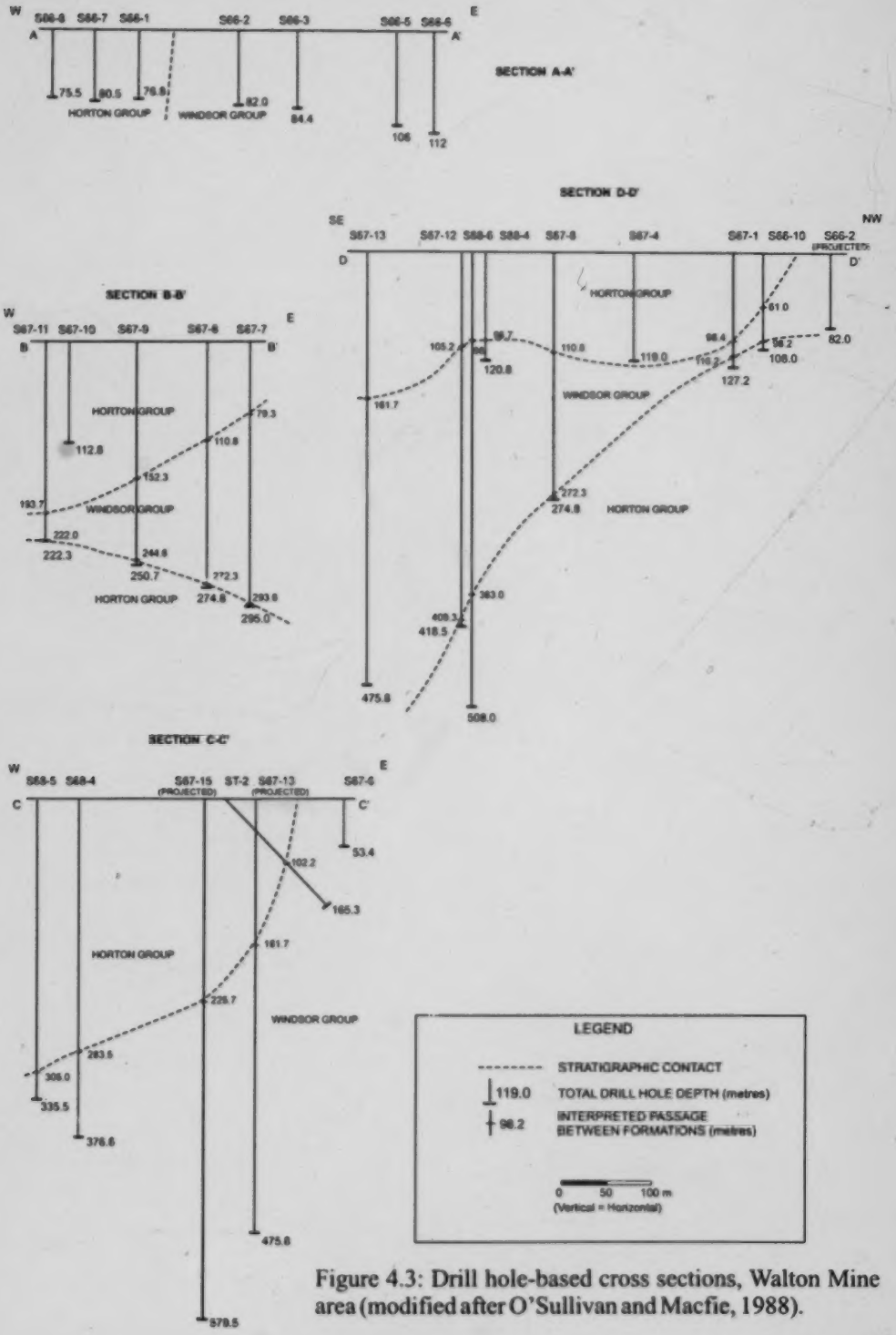


Figure 4.3: Drill hole-based cross sections, Walton Mine area (modified after O'Sullivan and Macfie, 1988).

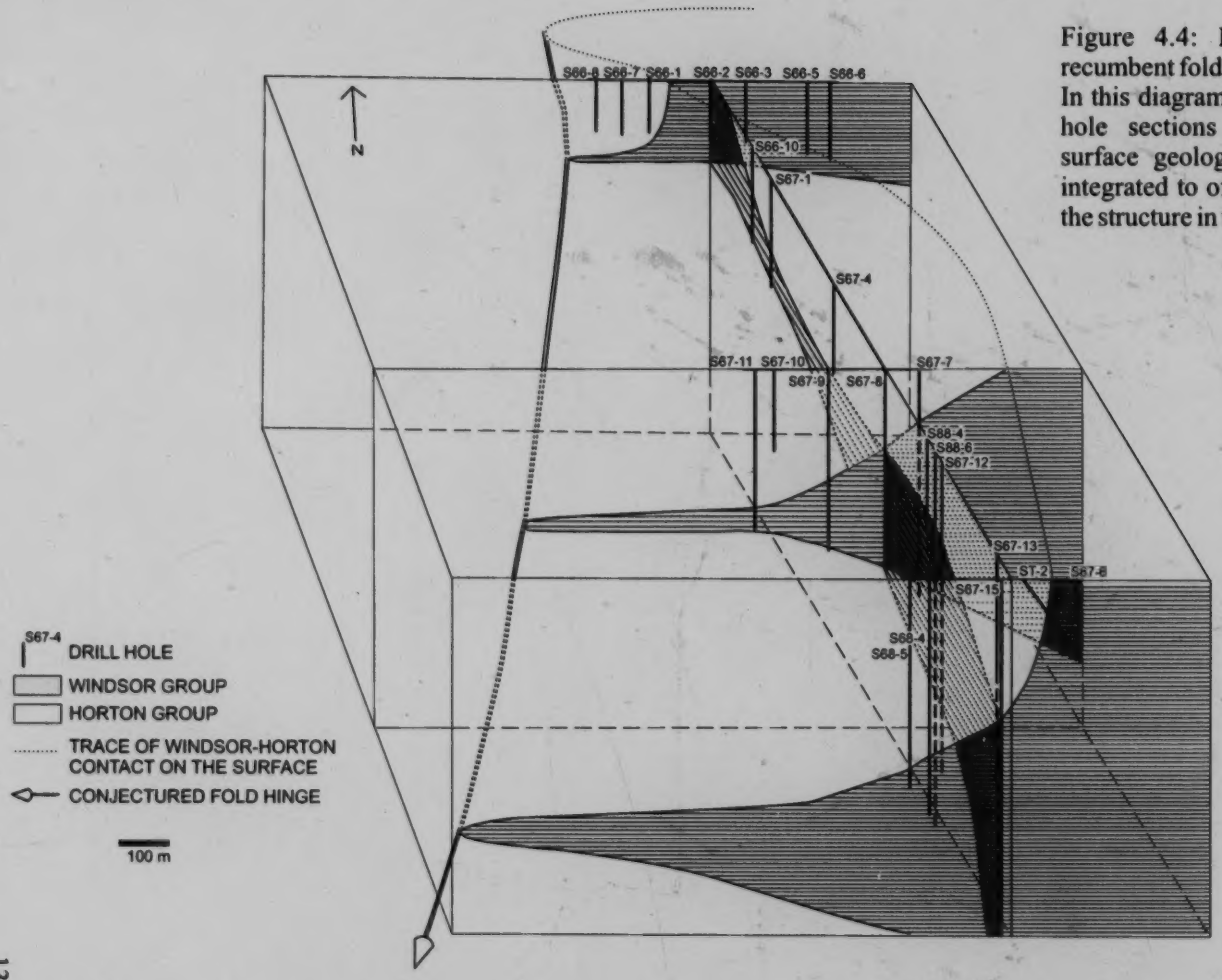


Figure 4.4: Fence diagram of recumbent fold, Walton Mine area. In this diagram, the data from drill hole sections (Figure 4.3) and surface geology (Figure 4.2) are integrated to offer a perspective of the structure in the area.

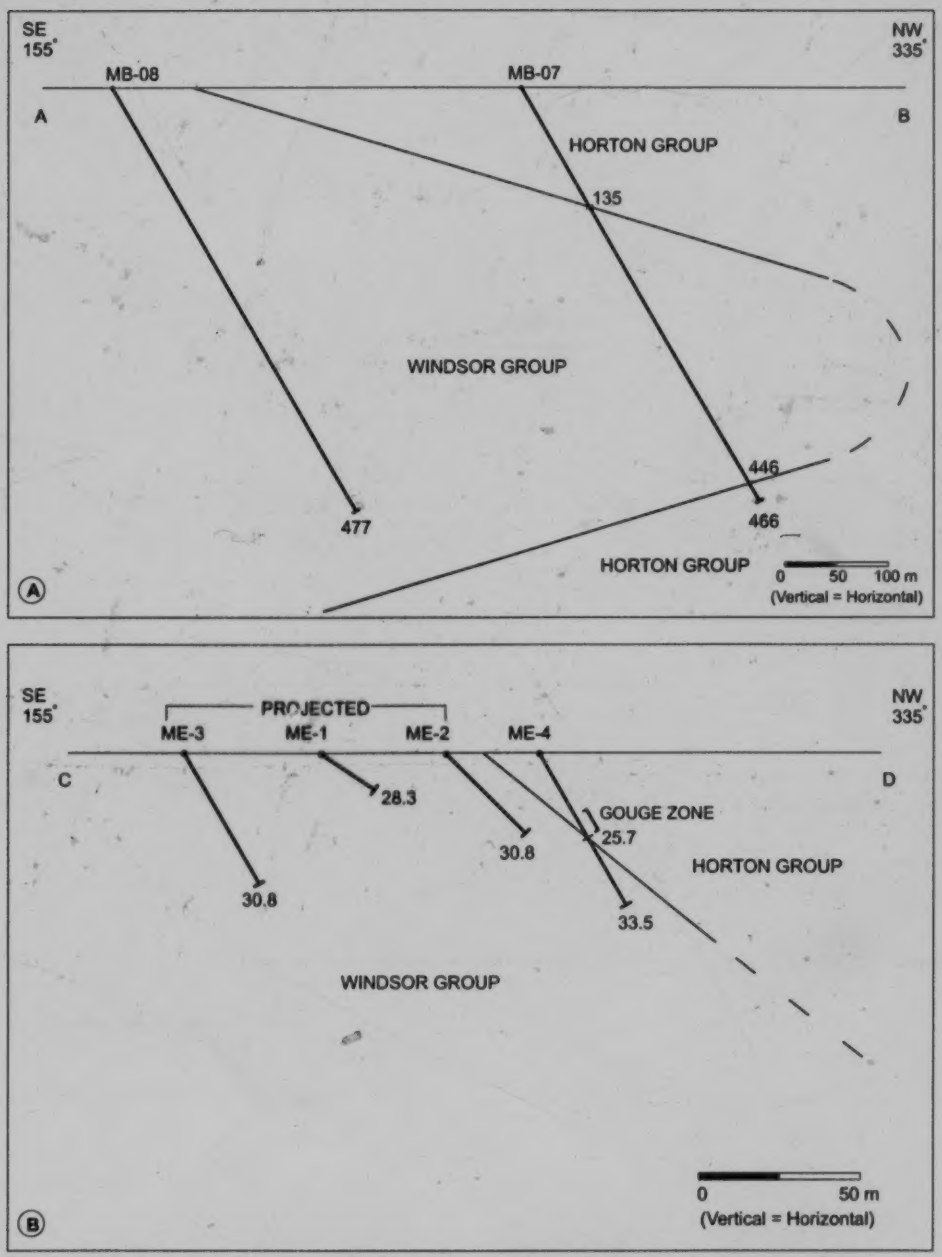


Figure 4.5: Interpreted reverse faults and recumbent folds based on subsurface information. A) Drill holes in Tennycape, possibly drilled through a large nappe, analogous to the structure suggested in the Walton Mine. (Modified after Black, 1995). B) A large gouge zone was intersected by drill hole ME-4 in the Summerville area, interpreted here as a result of reverse faulting.

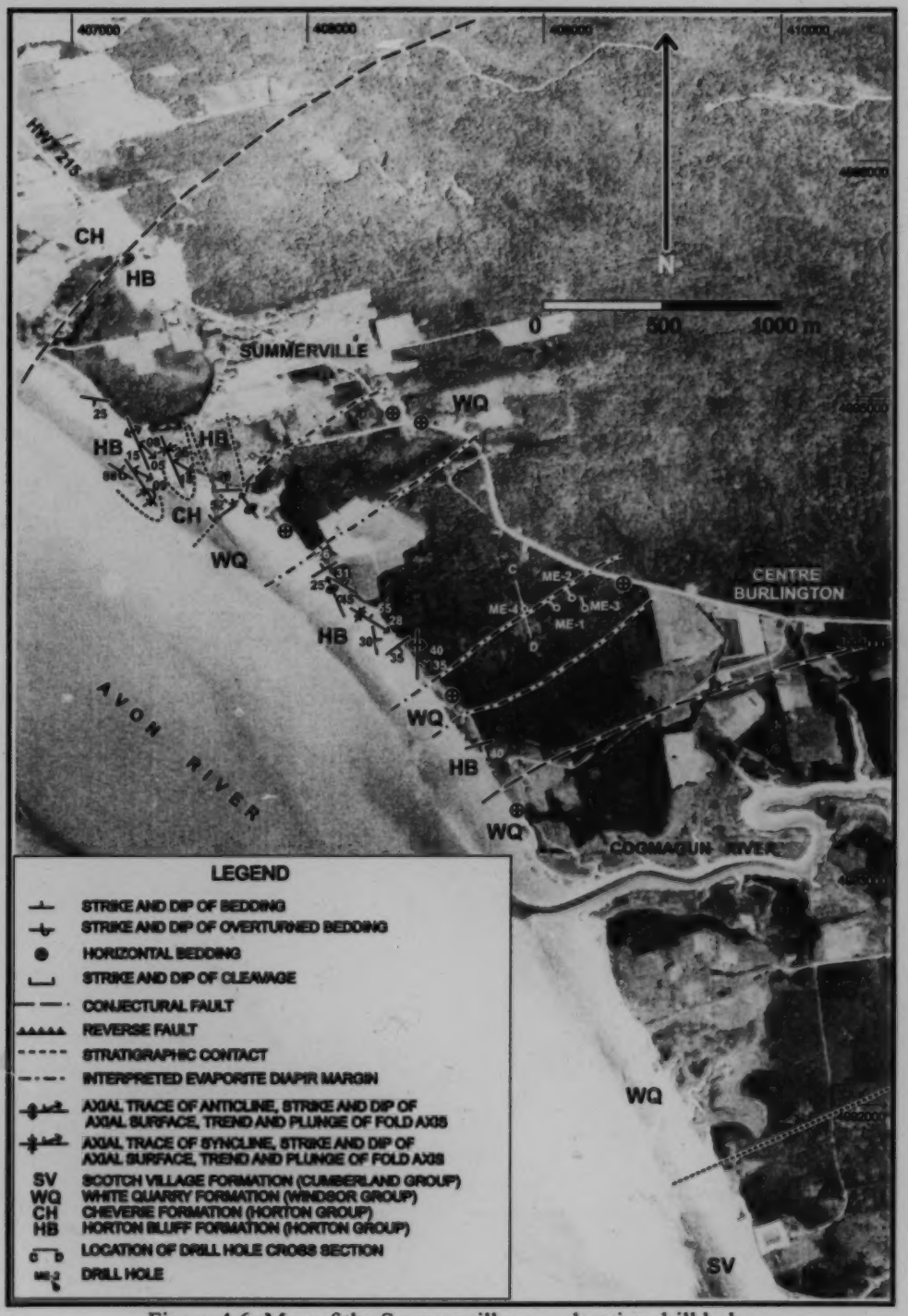


Figure 4.6: Map of the Summerville area showing drill holes.

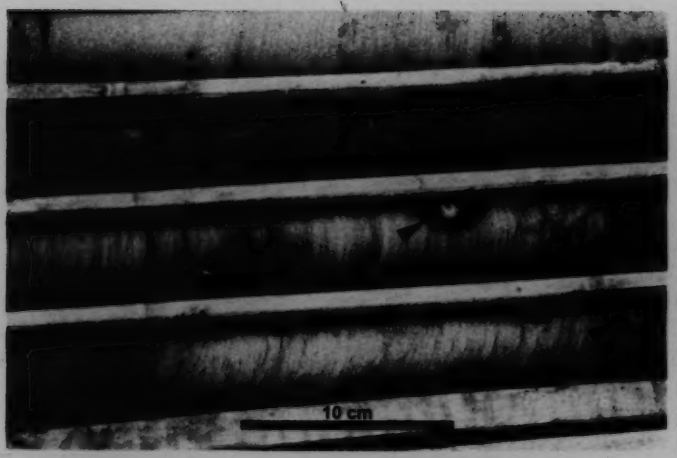
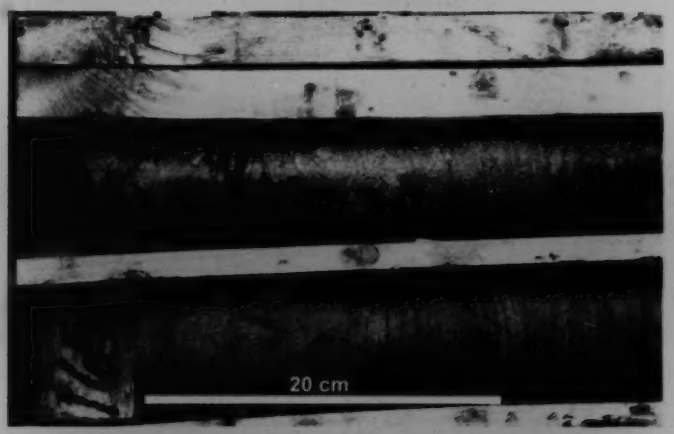


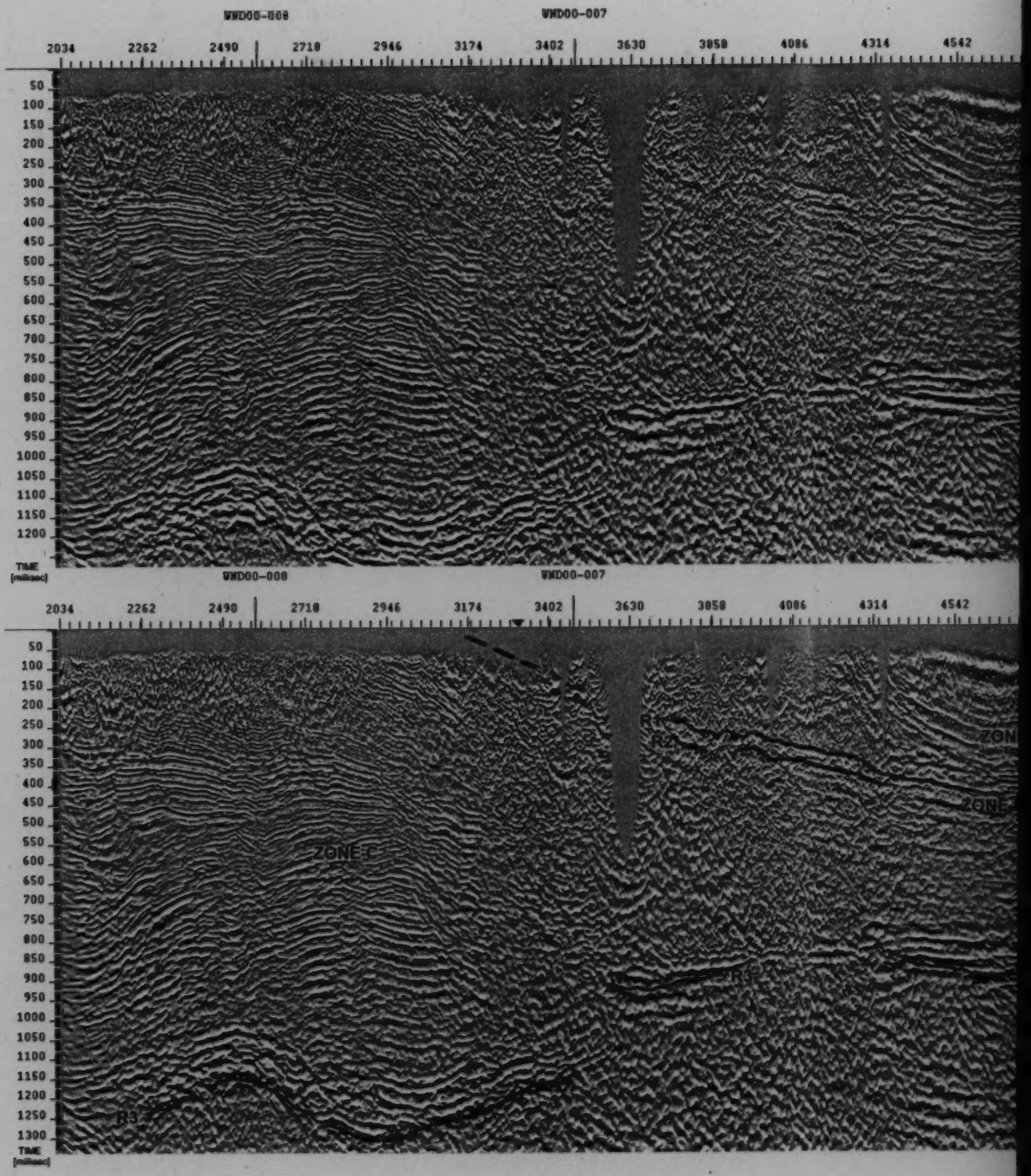
Figure 4.7: Core samples from drill hole STY93-1, Scotch Village Formation, Stanley area.

A) Undeformed sandstone and shale displaying planar lamination. Microcrystaline sulphides (arrows) alter the clastic rocks in places.



B) Conglomerate intervals were rarely observed and do not exceed 25 cm in thickness.

C) Plant debris and coal nodules that characterize the Scotch Village Formation. In this case, debris appear altered by pyrite and chalcopyrite in fine crystals.


VND00-008
VND00-007
2034
2262
2490
2718
2946
3174
3402
3630
3858
4086
4314
4542
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
TIME
[milisec]
VND00-008
VND00-007
2034
2262
2490
2718
2946
3174
3402
3630
3858
4086
4314
4542
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
TIME
[milisec]
R1
R2
R3
ZONE C
ZON
ZONE

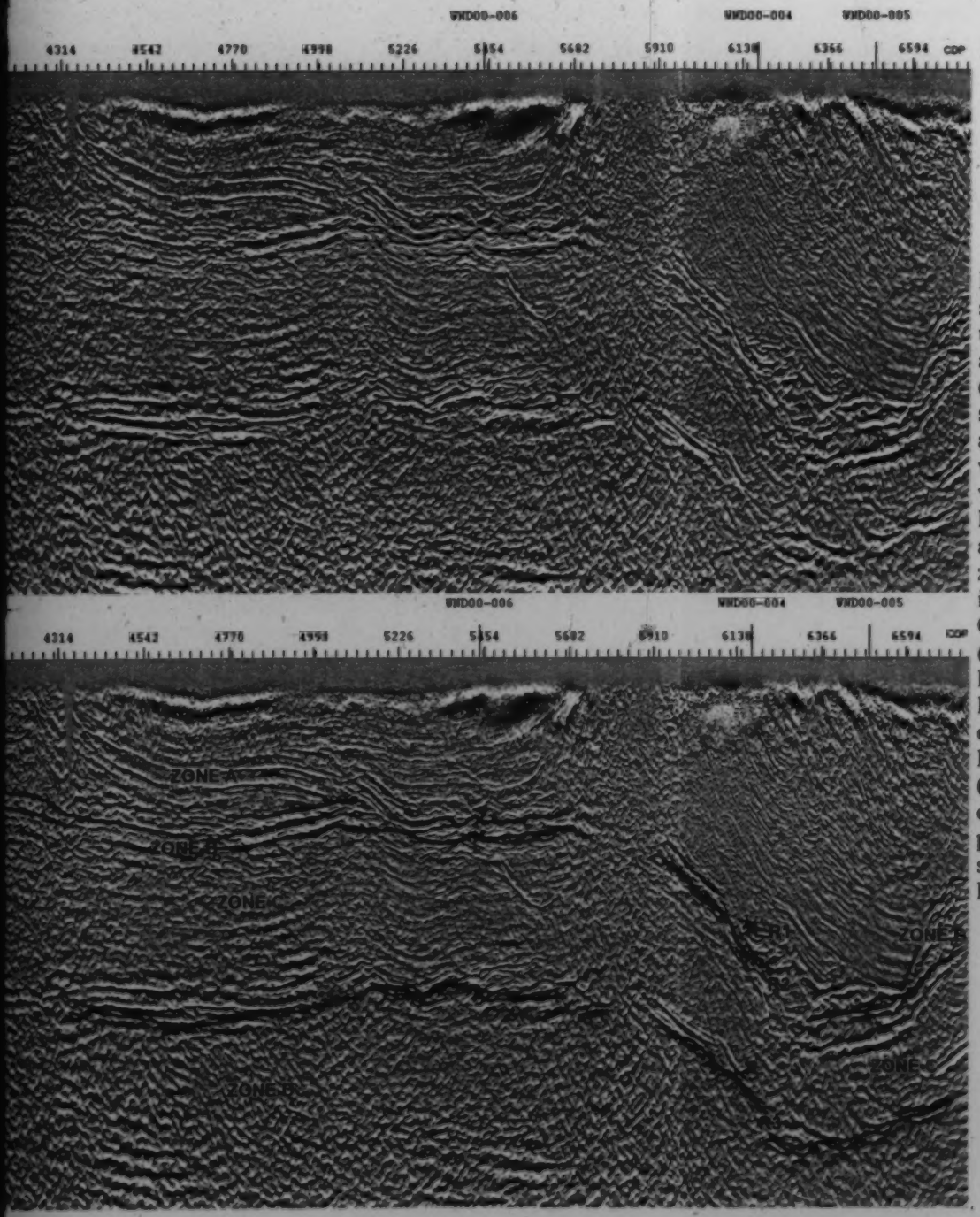
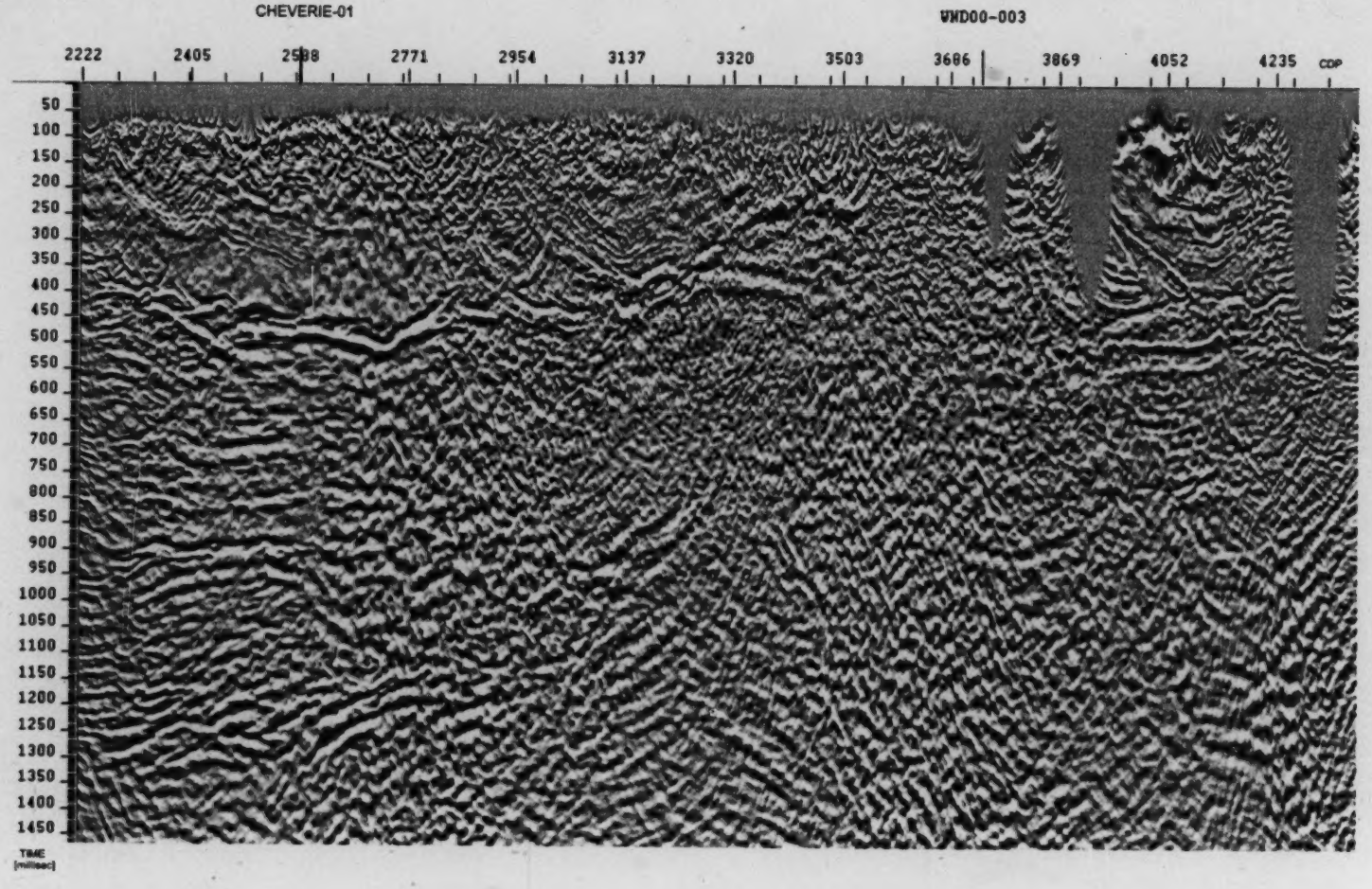


Fig. 4.8: Seismic section WND00-001, uninterpreted (above) and interpreted (below). Positive seismic responses appear in white, whereas negative values are dark grey. Reflections R1, R2, and R3 define three zones, here interpreted as White Quarry evaporites (zone A), Macumber limestone (zone B), Horton and Cheverie clastics (zone C), and Meguma basement (zone D). The thick dashed line suggests a prolongation to the surface of reflection R1.


CHEVERIE-01
WND00-003
2222
2405
2588
2771
2954
3137
3320
3503
3686
3869
4052
4235
CDP
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
TIME
[millisec]

WND00-003
2222
2405
CHEVERIE-01
2771
2954
3137
3320
3503
3686
3869
4052
4235
CDP
50
100

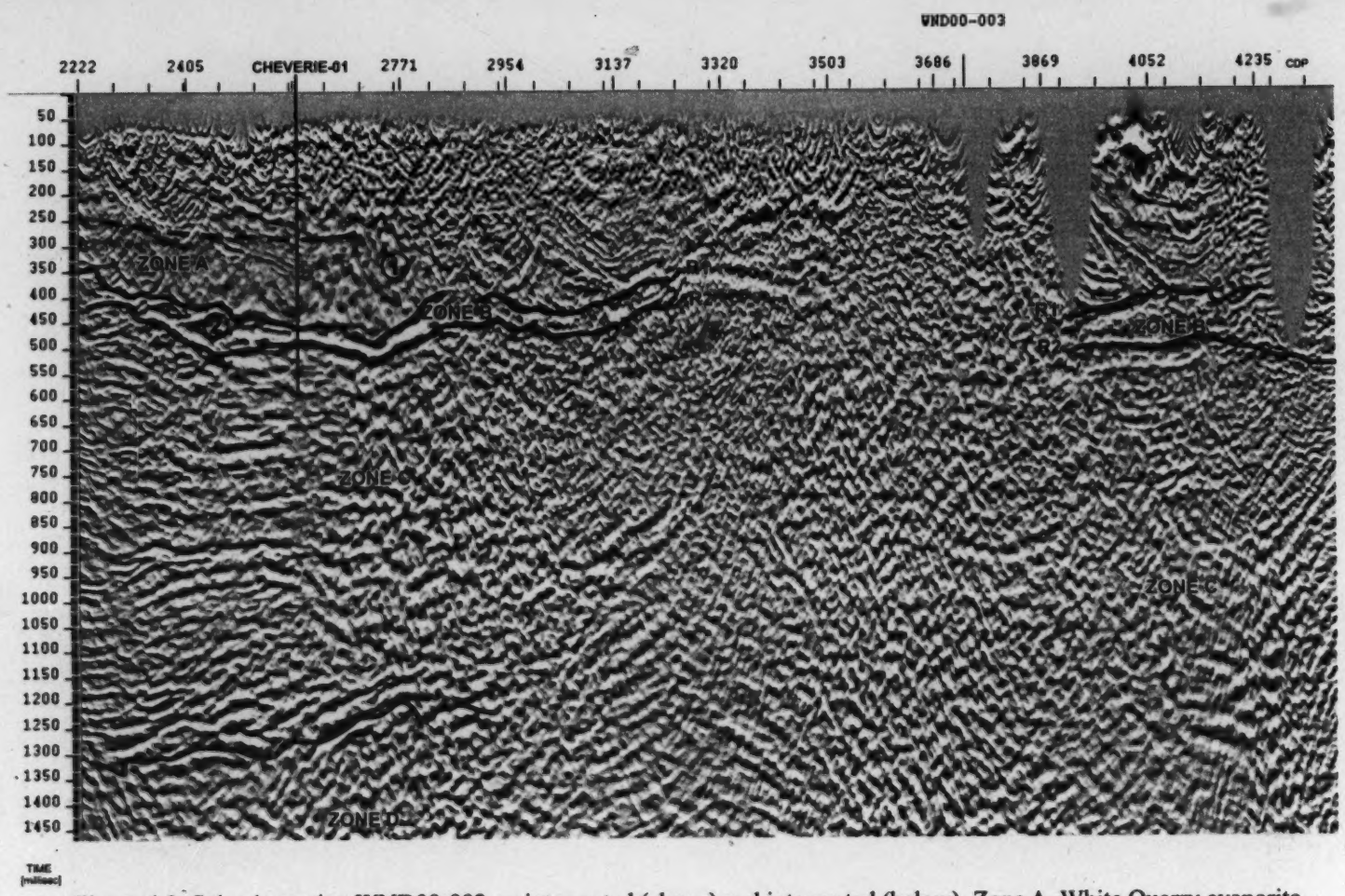
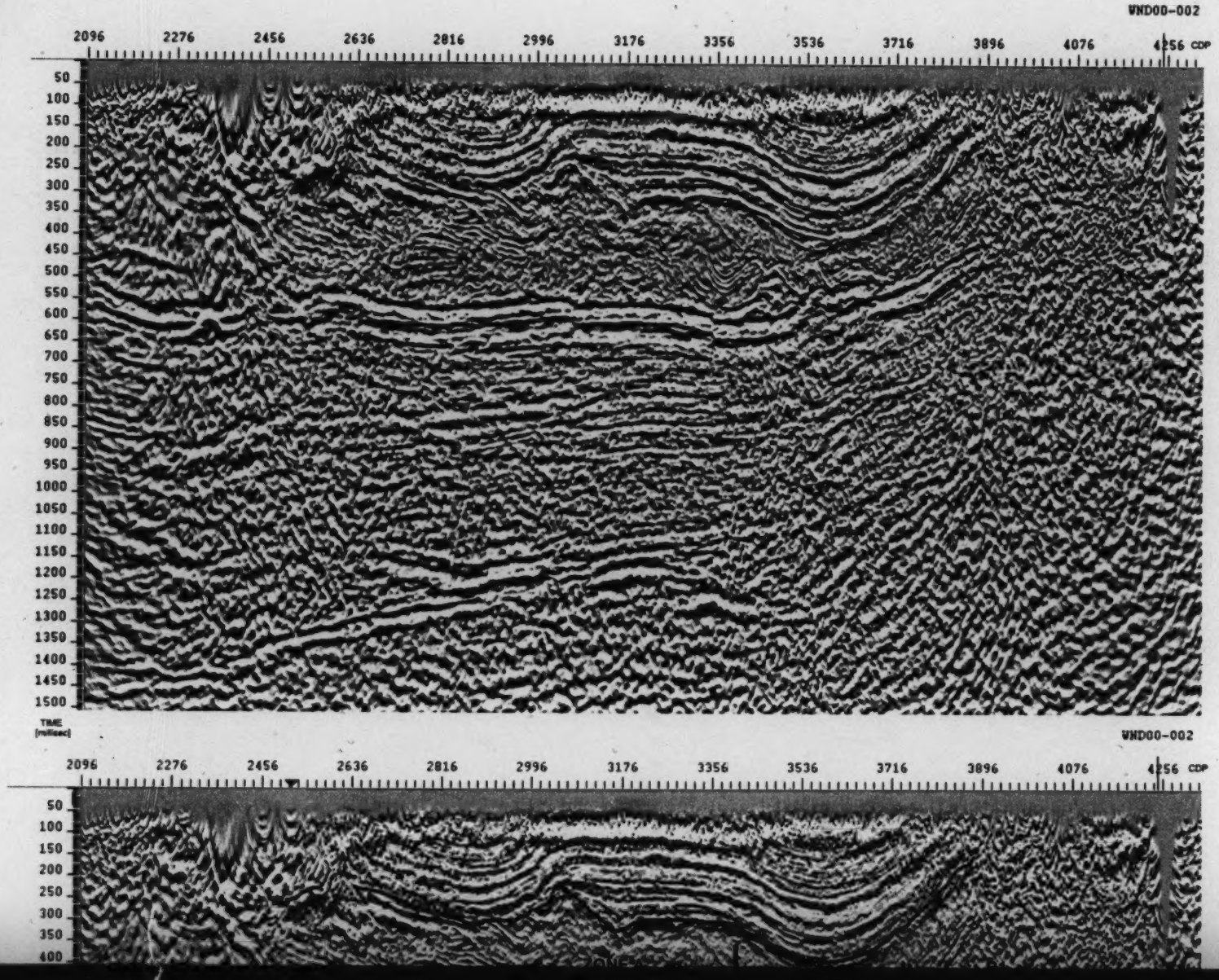


Figure 4.9: Seismic section WND00-002, uninterpreted (above) and interpreted (below). Zone A, White Quarry evaporite. Zone B, Macumber Formation. Zone C, Horton Group. Zone D, Meguma Group. Contorted pattern 1 possibly represents evaporites, as reported in previous works (Sheriff, 1989). Cross-cutting pattern 2 was interpreted as branched thrusts and duplexes. Lithologic log from Cheverie-01 well was correlated with the present section and projected (see 4.15). The dotted line represents the interpreted base of overthrusted Horton Group.


WND00-002
2096
2276
2456
2636
2816
2996
3176
3356
3536
3716
3896
4076
4256 CDP
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
TIME
[millisec]
WND00-002
2096
2276
2456
2636
2816
2996
3176
3356
3536
3716
3896
4076
4256 CDP
50
100
150
200
250
300
350
400

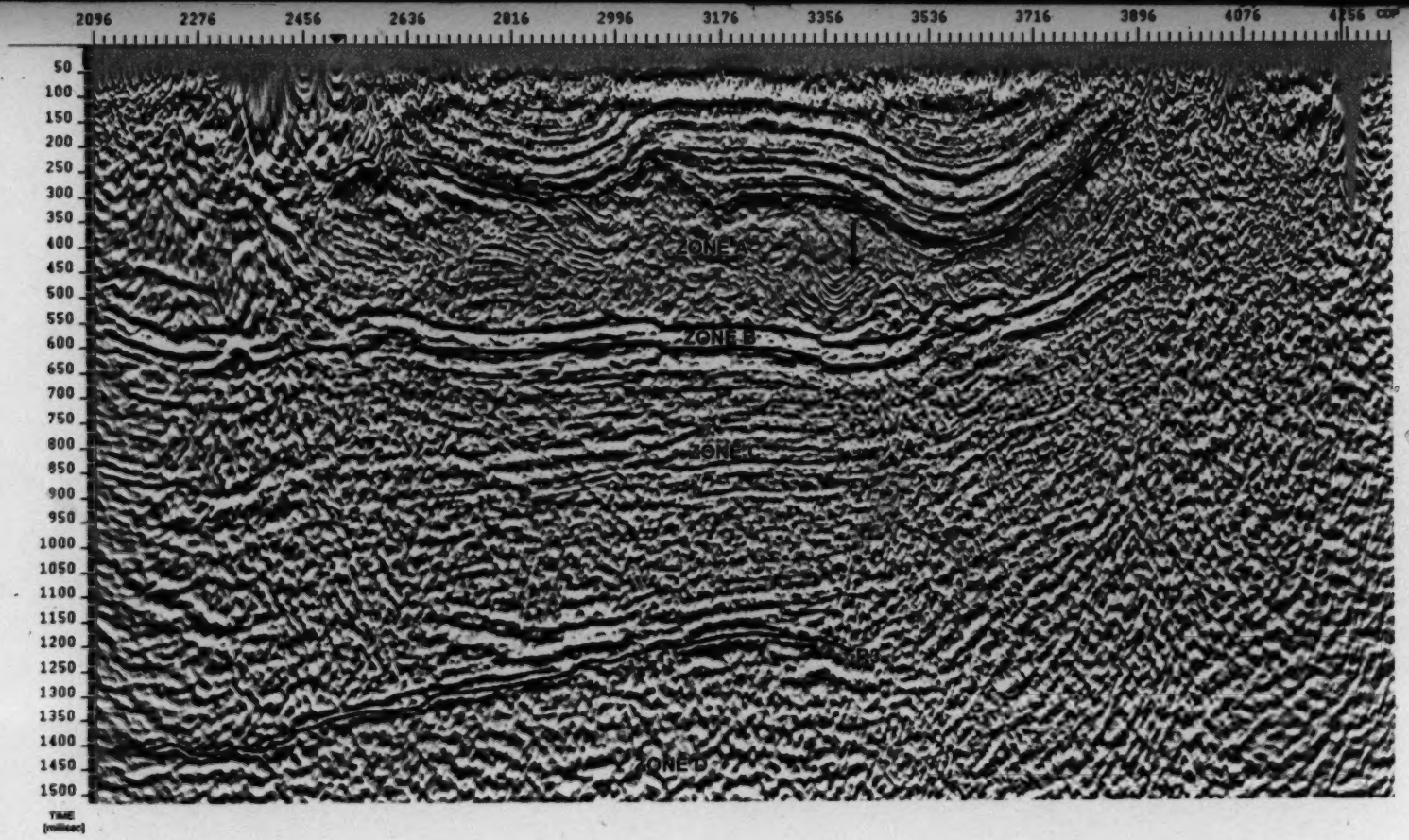
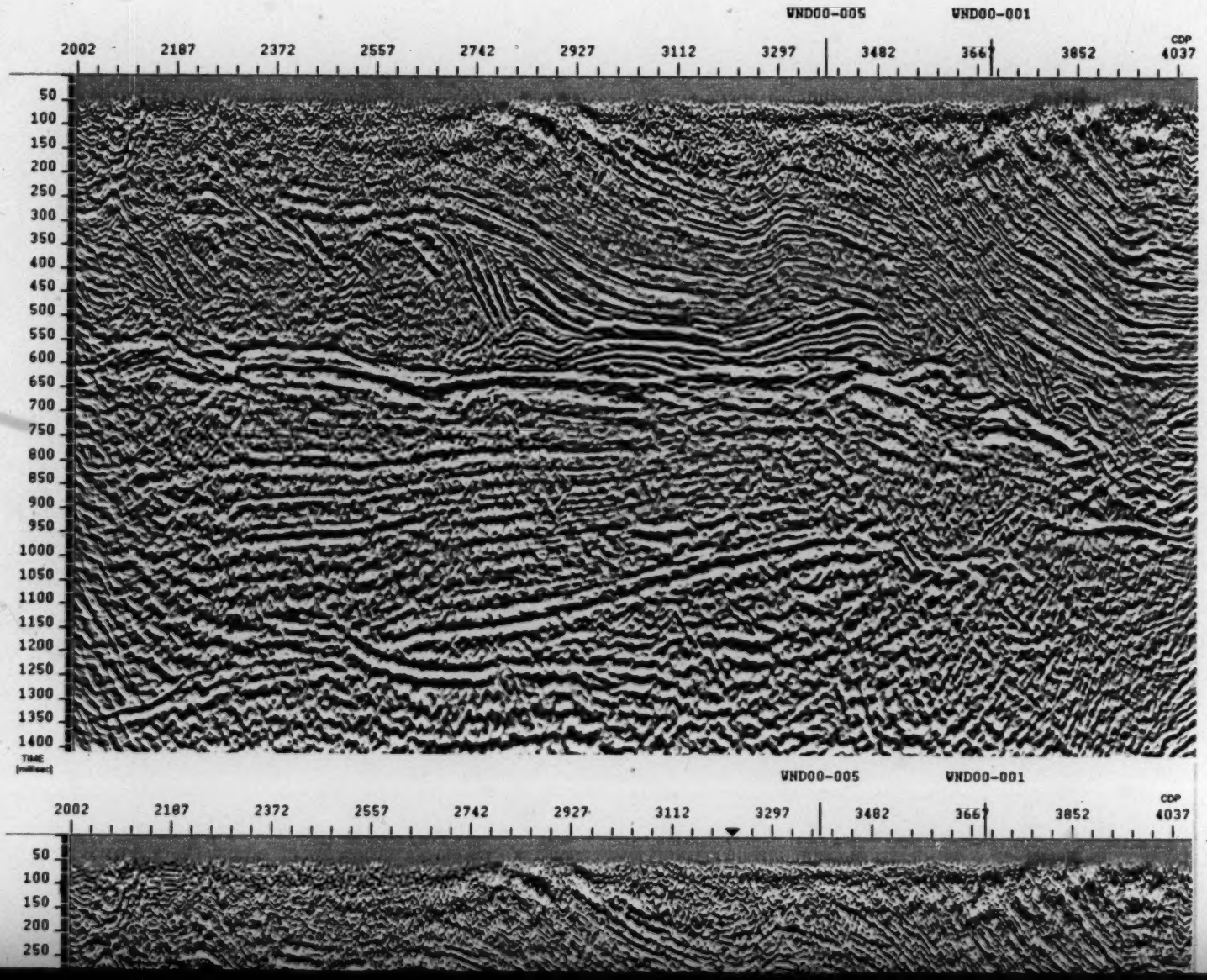


Figure 4.10: Seismic section WND00-003, uninterpreted (above) and interpreted (below). Zones A and B represent White Quarry and Macumber formations, respectively. Zone C is here interpreted as Horton Group. Irregular pattern (arrow) probably corresponds to evaporites. Upper thin solid line is proposed as the contact between Windsor (below) and Horton rocks (above). Stratigraphic repetition of the Horton Group is interpreted in Section 4.8.


WND00-005
WND00-001
2002
2187
2372
2557
2742
2927
3112
3297
3482
3667
3852
CDP
4037
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
TIME
[millisec]
WND00-005
WND00-001
2002
2187
2372
2557
2742
2927
3112
3297
3482
3667
3852
CDP
4037
50
100
150
200
250

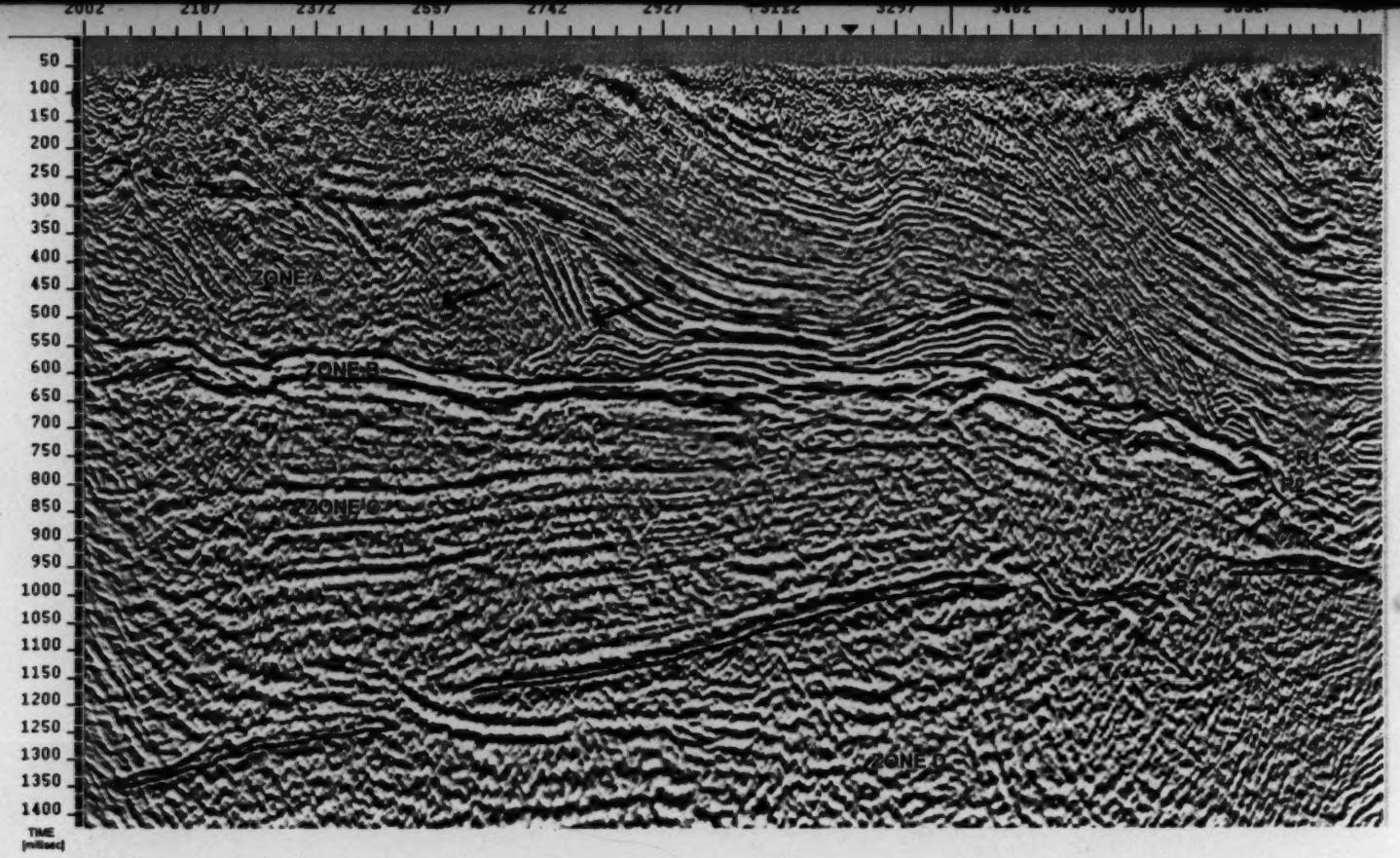
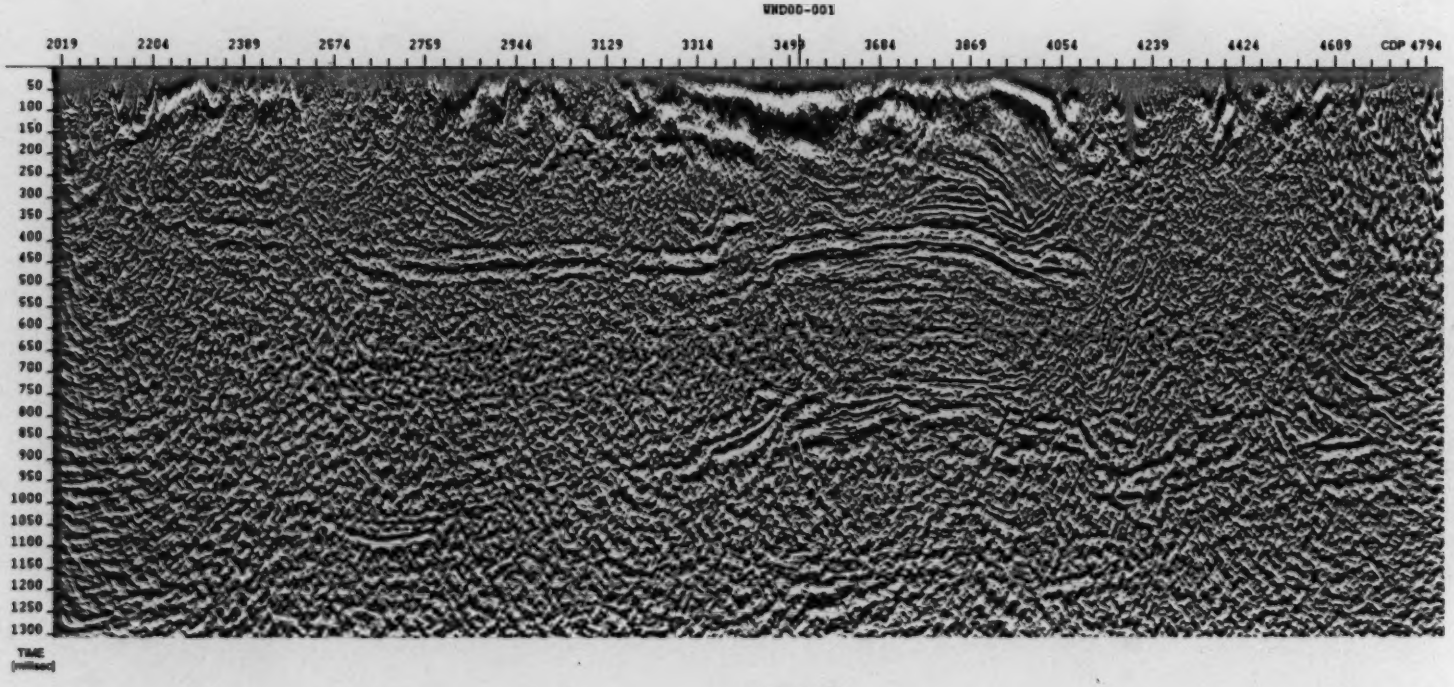
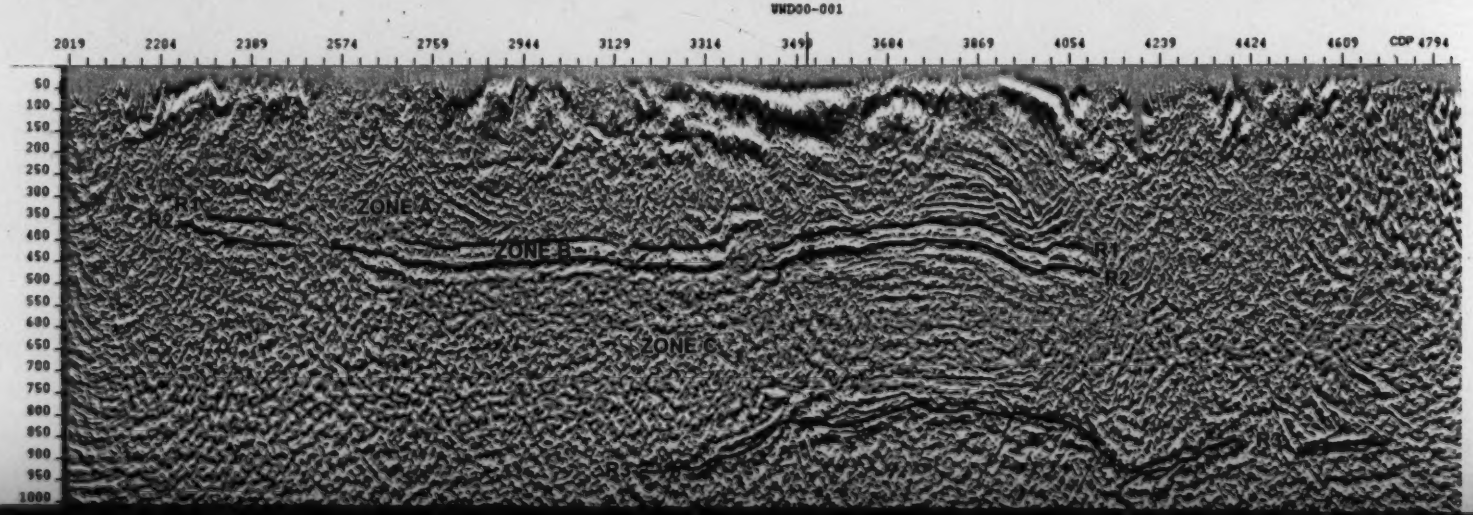


Figure 4.11: Seismic line WND00-004, uninterpreted (above) and interpreted (below). Zone A, White Quarry Formation. Zone B, Macumber Formation. Zone C, Horton Group. Zone D, Meguma Group. Upper dashed line is the suggested unconformity between the Windsor Group and allochthonous Horton Group (see Section 4.8 for an interpretation of the stratigraphic repetition). Dicontinuous reflections below the interpreted unconformity indicate complex structures at depth. Contorted patterns (arrows) possibly occur in response to White Quarry evaporite.


WND00-001
2019
2204
2389
2574
2759
2944
3129
3314
3499
3684
3869
4054
4239
4424
4609
CDP 4794
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
TIME
(millisec)


WND00-001
2019
2204
2389
2574
2759
2944
3129
3314
3499
3684
3869
4054
4239
4424
4609
CDP 4794
50
100
150
200
250
300
350
400
450
500
550
600
650
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900
950
1000
R1
R2
ZONE A
ZONE B
ZONE C
R1
R2
R1
R2

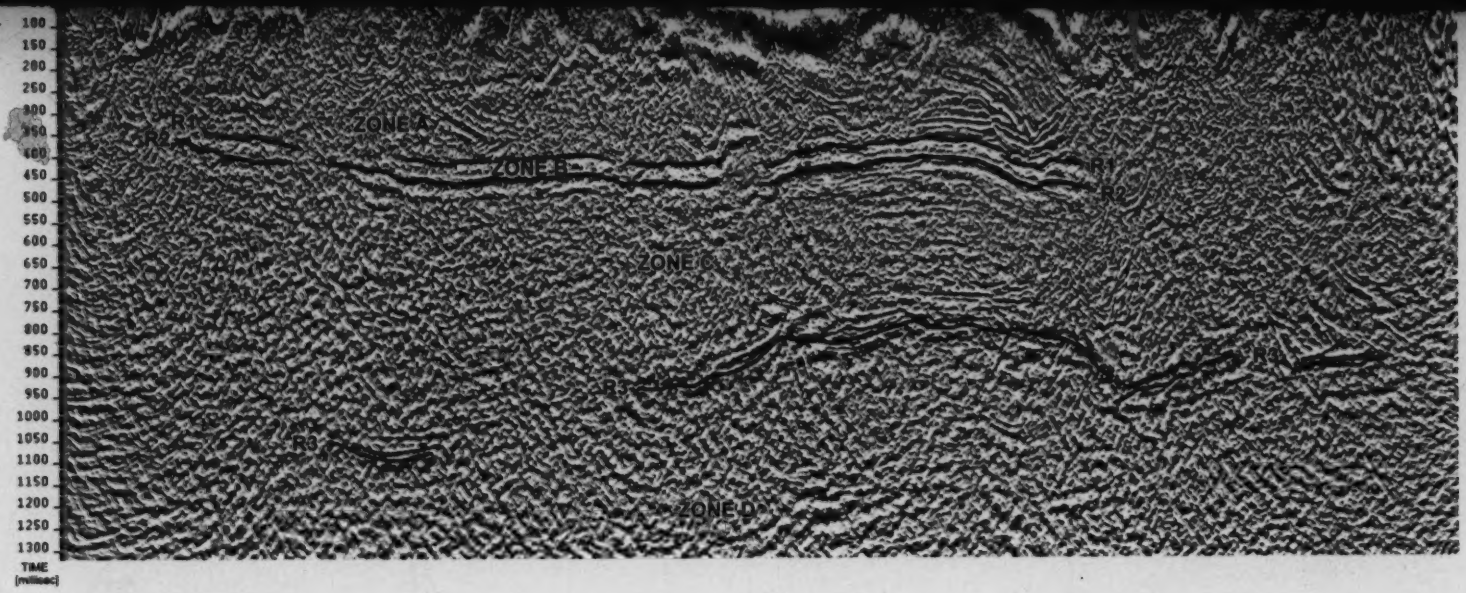
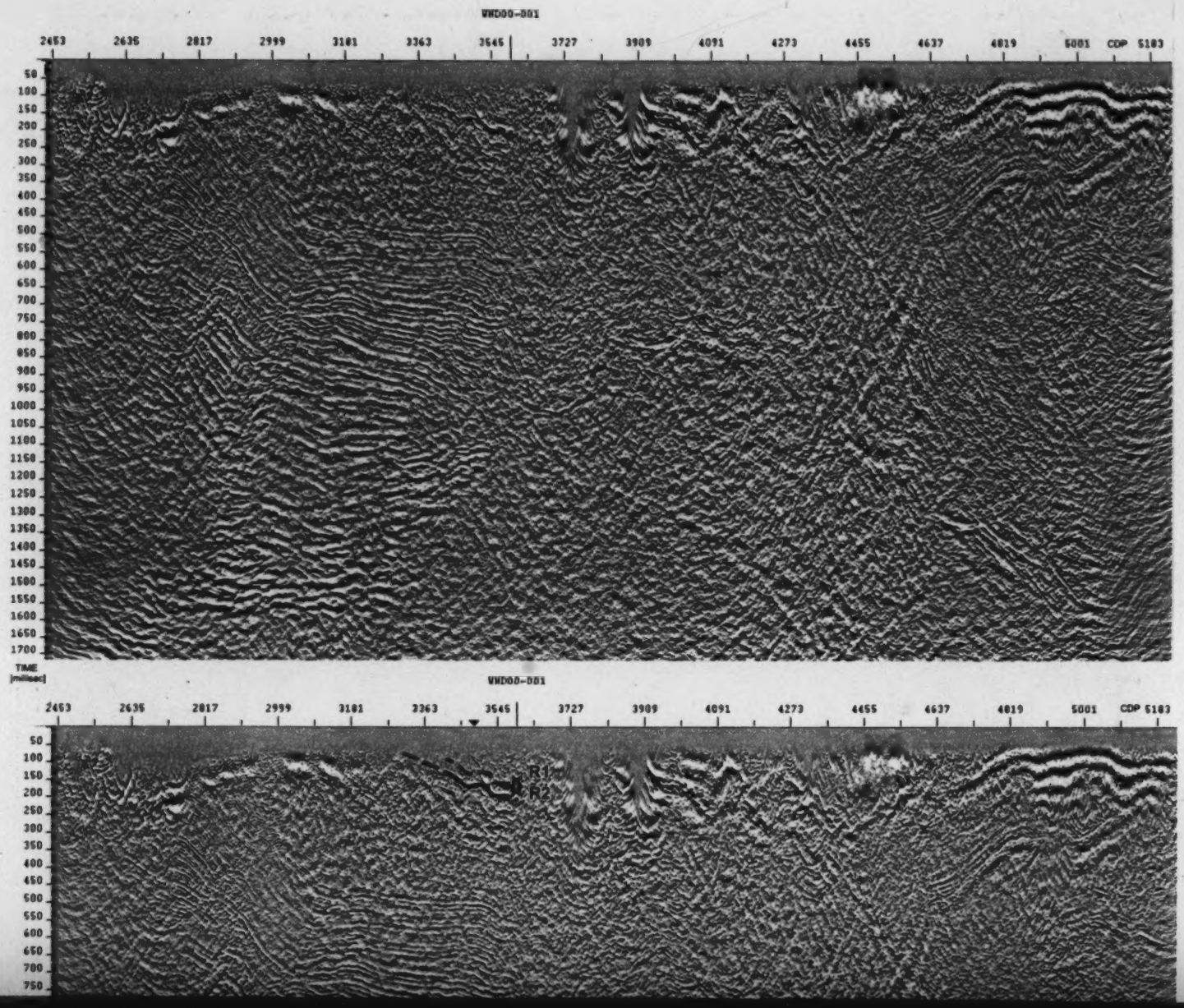


Figure 4.12: Seismic section WND00-006, uninterpreted (above) and interpreted (below). Reflections R1, R2, and R3 define three distinctive zones. Zone A, White Quarry Formation. Zone B, Macumber Formation. Zone C, Horton Group. Zone D, Meguma Group.


WWD00-001
2453
2635
2817
2999
3181
3363
3545
3727
3909
4091
4273
4455
4637
4819
5001
CDP 5183
TIME [millisec]
R1
R2

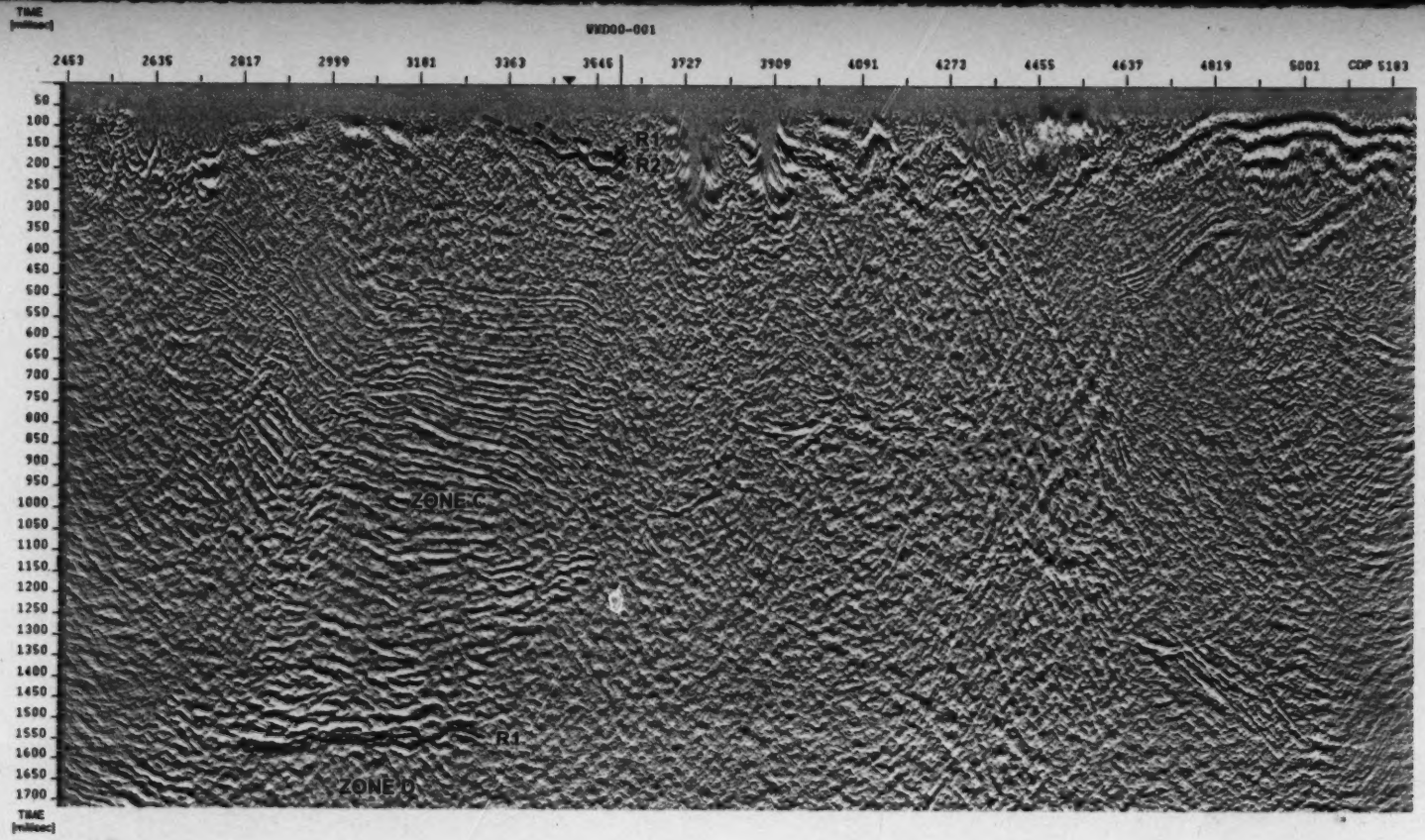
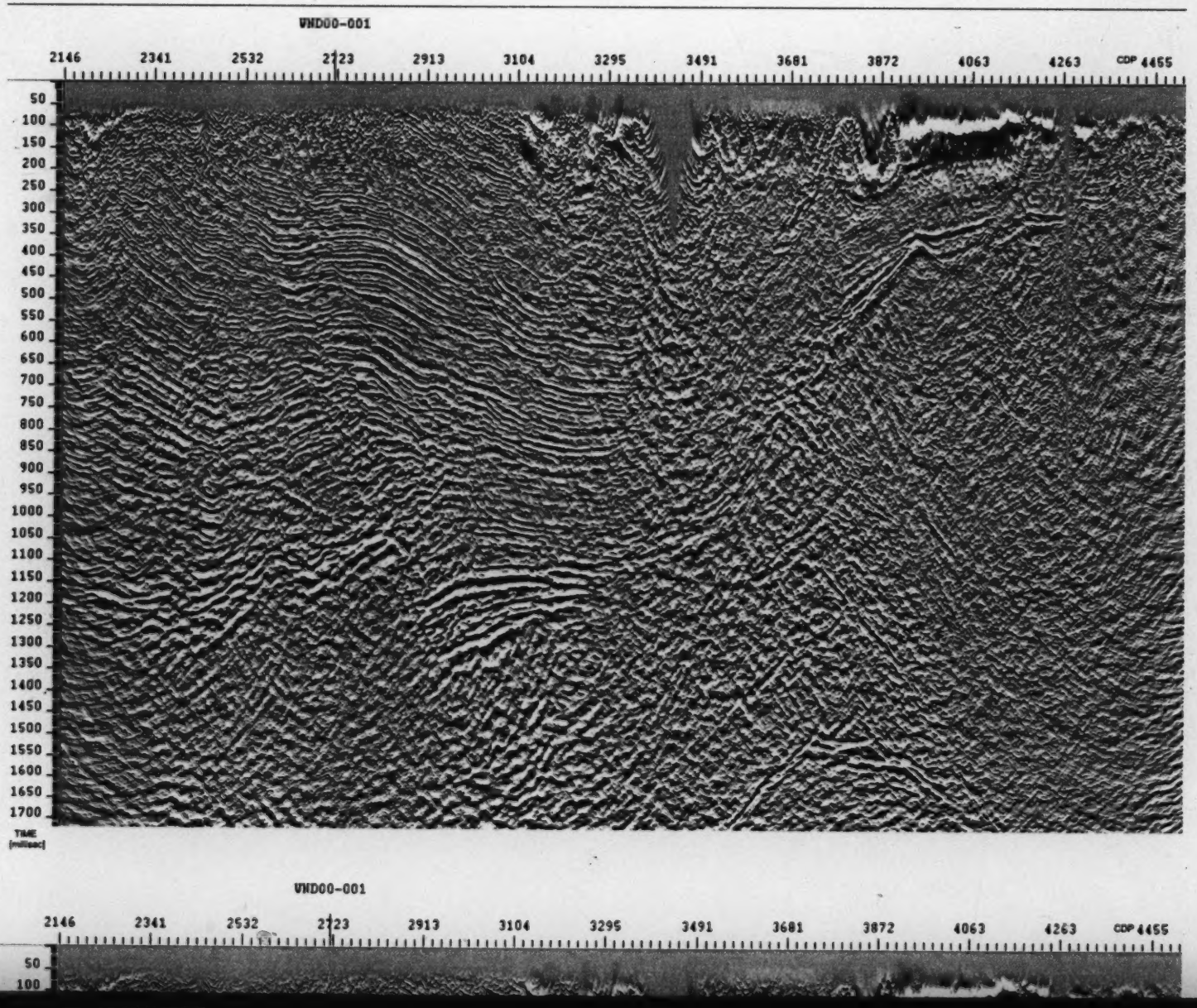


Figure 4.13: Seismic section WND00-007, uninterpreted (above) and interpreted (below). Zone C, interpreted as Horton Group, appears as a thick, continuous sequence from the basement (Zone D) to the surface, contrasting with sections at the west. Two possible reflections defining the Macumber Formation are suggested based on the interpretation of Section WND00-001, which cross-cuts line WND00-007.


VND00-001
2146
2341
2532
2723
2913
3104
3295
3491
3681
3872
4063
4263
CDP 4455
50
100
150
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150
1200
1250
1300
1350
1400
1450
1500
1550
1600
1650
1700
TIME
[millisec]
VND00-001
2146
2341
2532
2723
2913
3104
3295
3491
3681
3872
4063
4263
CDP 4455
50
100

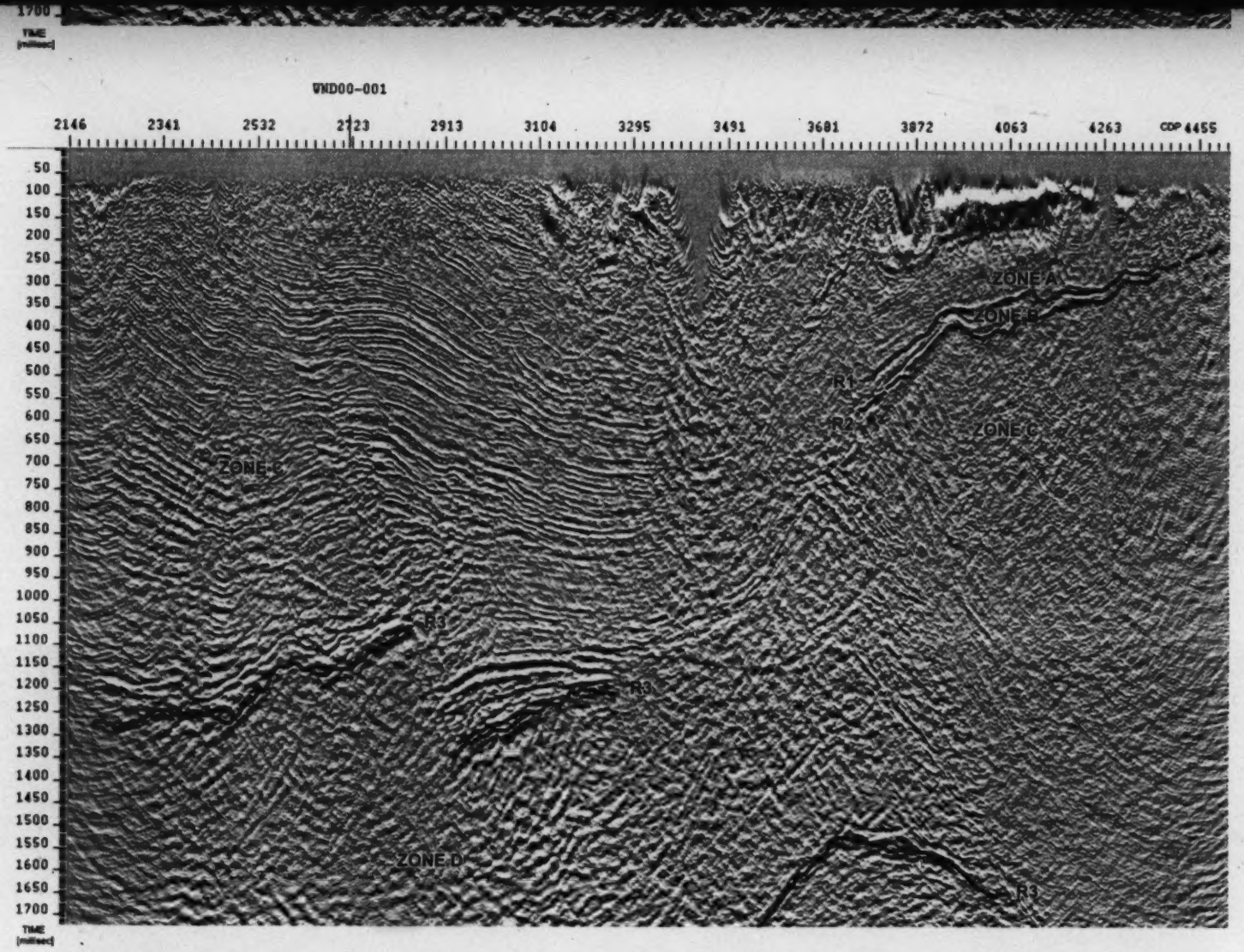
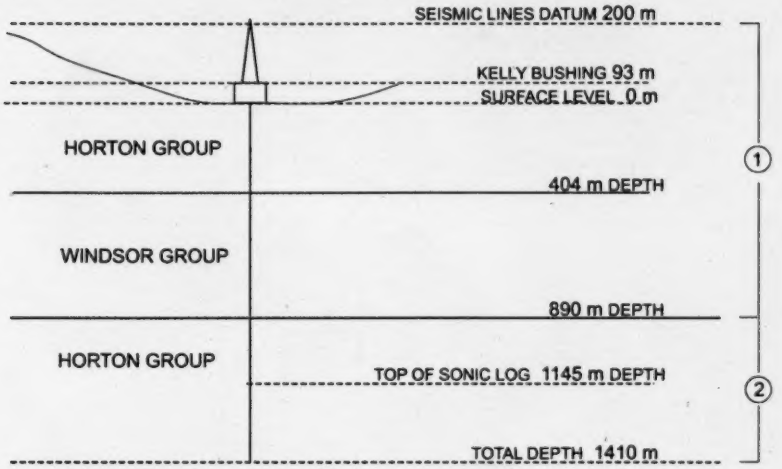


Figure 4.14: Seismic section WND00-008, uninterpreted (above) and interpreted (below). Zone C (Horton Group) appears as a thick and continuous succession from the basement (Zone D, Meguma Group) to the surface. Important discontinuities suggest the presence of major faults, some of them affecting the basement. Zones A and B represent White Quarry evaporite and Macumber limestone, respectively.

CHEVERIE-01 WELL DIAGRAM (TOTAL DEPTH: 1410 m)
CORRELATION WITH SEISMIC LINE WND00-002



AVAILABLE LOGS

CUTTING: 30-1410 m
CORE: 1243-1350 m
SONIC: 1145-1410 m

NOT IN SCALE

MEAN CALCULATED VELOCITIES FOR INTERVALS 1 AND 2

(1) - INTERVAL 1 CONSISTS OF SOIL, HORTON AND WINDSOR ROCKS (SONIC LOG NOT AVAILABLE
- TWO-WAY-TIME (TWT) FROM THE KELLY BUSHING TO THE BASE OF THE WINDSOR GROUP (FROM SEISMIC SECTION WND00-002): 490 milliseconds (ms)
- BASE OF THE WINDSOR GROUP (FROM CUTTING LOG): 890 m

-MEAN VELOCITY :
[(200-93)+890]m x 2 / [490ms/0.001s] = 4069 m/s

-COMPARABLE LITHOLOGICAL AVERAGE VELOCITIES (SHERIFF, 1989):
SANDSTONE/SHALE, 3000 m/s
LIMESTONE, 4500 m/s
GYPSUM, 6000 m/s
-THESE VALUES SUGGEST THAT THE ESTIMATED MEAN VELOCITY FOR INTERVAL 1 IS REASONABLE.

(2) -INTERVAL 2 CONSISTS OF HORTON ROCKS
-THE ACOUSTIC VELOCITY FOR HORTON STRATA CAN BE OBTAINED FROM THE SONIC LOG RUN (1410-1145 m). THIS VELOCITY IS APPLICABLE FROM 890 TO 1410 m BECAUSE THE SAME LITHOLOGY IS INVOLVED.

-MEAN VELOCITY FROM SONIC LOG: 215 MICROSECONDS/METRE = 4651 m/s

TO PROJECT THE CHEVERIE-01 WELL INTO SECTION WND00-002, TWT FOR INTERVALS 1 AND 2 MUST BE ADDED:

TOTAL TWT = TWT1 + TWT2 = 490 ms + [(1145-890)m + (1410-1145)m] / 4651 m/s] = 602 ms

Figure 4.15: Correlation and migration in time of Cheverie-01 well into seismic section WND00-002.

5. General Discussion

5.1. Map scale evidence for thrust tectonics

Competing hypotheses about the origin of the rocks mapped as Horton Group were presented in Section 4.8. Clastic rocks containing characteristic Horton Group fossils occur in the coast and inland areas, from Summerville to Lower Selma. Sandstones and shales identified as Horton Group also occur in mining drill holes and oil well logs drilled inland. In Section 4.7 seismic sections were interpreted regionally in the area of study as indicating that in many locations the Horton Group overlies the Windsor Group. Since strata of the Horton Group have been observed and interpreted above the Windsor Group not only at the surface, but also at depth, it is likely that part of the mapped Horton Group has been transported a few kilometers.

The upper interval of Cheverie-01 oil well and outcrops of clastic rocks in the coast of the study area were interpreted as Scotch Village Formation by McDonald (2001). However, palynological examination of samples from the upper intervals of well Cheverie-01 and the coast, demonstrate that the units mapped as Horton Group were correctly interpreted (Utting, 2002a, 2002b). In order to verify the difference between the Horton Bluff Formation and the Scotch Village Formation, outcrops of the Scotch Village Formation were observed in the banks of the Kennetcook River and seen to be undeformed successions (Section 3.1). In addition, undisturbed successions of the Scotch Village Formation were reported by Boehner and Edgecombe (1993) in exploratory drill hole STY93-1 (Section 4.5). These

observations suggest that the Scotch Village Formation was not affected by the same strain that deformed the transported Horton Group.

Boehner (1991) interpreted seismic lines run by Chevron Canada Ltd. from the coast between Tennycape and Minasville, up to 15 km south. He concluded that a low angle, northerly-dipping thrust fault transported the Horton Group on top of Windsor Group in the coastal area. Boehner (1991) interpreted that the thrust surface crops out inland, 2 to 7 km south of the coast. The concept of a thrust surface dipping to the north is consistent with the present interpretation. In addition, about 7 km north of Summerville, Johnston (1999) proposed a low angle fault zone that placed allochthonous Horton Bluff Formation over younger Cheverie Formation and Windsor Group rocks (Section 1.2). However, the subsurface data analyzed in Chapter 4 indicates that the interpreted regional thrust is blind, i.e. it does not reach the surface, when traced in the subsurface to the southeast (Fig. 5.1, Fig. 5.2).

Horton and Windsor rocks that appear relatively undeformed near the coast in the Cheverie area (Fig. 4.1, Fig. 5.1, Fig. 5.2) were mapped by Moore (1986) and Johnston (1999). Most contacts were interpreted as tectonic (Moore, 1986). Because of their undisturbed successions and their inferred contacts in the field, it is possible that these rocks represent a combination of evaporite diapiric structures and tectonic windows (Fig. 5.1, Fig. 5.2).

In order to interpret the extent of allochthonous Horton rocks in the area farther east from Tennycape to Selma, two hypotheses are presented. In this area, seismic lines WND00-007 and 008 (Fig. 4.13, Fig. 4.14) suggest that the Horton Group is a continuous succession from the basement to the surface, apparently not transported

on top of Windor evaporites (Section 4.8). However, if the thrust surface occurs closer to the surface than in areas to the west (Cheverie, Walton), the limited resolution of seismic data at shallow depths would make it difficult to interpret transported Horton strata. The first hypothesis is that the Horton Group cropping out from Mutton Cove to a point near Noel is allochthonous, whereas Horton rocks from Noel to Selma are autochthonous (Fig. 5.1 A, B). In this interpretation, the Old Quarry represents a zone of thin strata of overlying Windsor evaporite. The second hypothesis is that the Horton Group mapped in the coast from Mutton Cove to Selma is allochthonous. Windsor outcrops in the Old Quarry zone would represent a tectonic window through which the Macumber limestone and White Quarry anhydrite are observed (Fig 3.41, Fig. 4.1). The lack of shallow mining drill holes and detailed mapping in the east portion make it difficult to choose between these hypotheses.

Thrust surfaces are suggested by the surface geology and the subsurface data. Horton Bluff Formation shales display asymmetric fabrics in the Summerville area (Chapter 3). The kinematic interpretation of asymmetric fabrics suggest southward transport, consistent with the proposed regional thrust zone of Horton Group on top of Windsor Group (Fig. 3.5). Mining drill holes in the Summerville area support the thrust relationship between Horton and Windsor strata (Section 4.4).

5.2. Character of deformed Lower Windsor units.

Salt, anhydrite, and certain types of shale can act as a lubricant between strata if the basement is not involved in the deformation (Jenyon, 1986; Jackson, 1995). The classic example of evaporites as detachment surfaces occurs in the Jura Mountains of the Alps (Buxtorf, 1907; Ramsay, 1963; and many others). Among other examples, the Southeastern Pyrenees (Saez and Riba, 1986; Sans and Verges, 1995; Verges and Burbank, 1996) and the Kohat Plateau (Pivnik and Sercombe; 1993) demonstrate that the geometry of thrust belts can be controlled by weak salt detachment surfaces. The easiest propagation is achieved along the low-resistance evaporite layer, allowing the deformation of the more competent overlying successions to be transmitted far away. Transport of overlying successions is achieved through detachment folds, nappes, and thrusts.

Gypsum and anhydrite of the White Quarry Formation are here interpreted as having provided a detachment surface for the proposed regional overthrust of the Horton Group. The proposed regional thrust zone probably consisted of more than one main detachment level. Subordinate halite and shale of the Windsor Group, reported in drill hole STY93-1 and well Cheverie-01 (Boehner, 1994; McDonald, 2001), possibly acted as additional detachment levels. Curving and cross-cutting patterns observed in seismic lines (Fig. 4.11) could be representing branched thrusts, duplexes, and reverse faults in the Windsor Group.

In the Walton Mine subarea, an outcrop-scale nappe has been inferred after the construction of several cross sections (see Section 4.2). This nappe is interpreted as having transported allochthonous rocks in addition to the proposed regional thrust

surface at depth. Overturned to recumbent fold nappes are associated with thrust sheets in areas where evaporites played an important role. Fold nappes occupying thrust sheets that have moved 10 km or more, relative to footwall rocks, are found in the Jura (Jordan and Noack, 1992).

Salt dome structures probably developed regionally after the thrust that placed Horton Group on top of Windsor Group. In the Summerville area, contacts between Windsor and Horton strata are subvertical, while gypsum fibres in tension gashes are vertical or plunge steeply (see Chapter 3). These observations are consistent with subvertical emplacement of evaporite domes. Convoluted patterns were observed in seismic sections WND00-004 and 002, in the west portion of the study area (Fig. 4.9, Fig. 4.11). These patterns probably reflect evaporite diapirs developed in large zones at depth.

Limestone units in the base of the Windsor Group include breccias, most of which is the Pembroke Breccia. The Pembroke Breccia appears associated with the Macumber Formation in outcrops and drill holes in the base of the Windsor Group (Sections 1.2, 2.2.1, and 4.2). The origin of the Pembroke Breccia in the area of study has been a subject of debate (Clifton, 1967; Geldsetzer, 1977; Lynch and Giles, 1993). Dissolution features on limestone clasts, oxidized carbonate matrix, high porosity, and variable sedimentary trends (coarsening and fining-upward) have been recorded in outcrops and drill holes in the Walton Mine and Pembroke areas (Lavoie et al., 1995). The Pembroke Breccia has been interpreted as a karst and solution-collapse breccia, resulting from dissolution of the limestone-evaporite succession of the Macumber Formation (Lavoie et al., 1995).

Limestones of the Macumber Formation and Pembroke Breccia show abrupt changes in thickness at depth in Summerville, Walton Mine, and Tennycape (see Sections 4.2, 4.3, 4.4). Macumber limestones may have contained bioherms, which as primary features could cause moderate changes in thickness (Boehner et al., 1989). However, seismic sections WND00-004 and 002 (Fig. 4.9, Fig. 4.11) display reflections that probably represent discordant relationships among layers in the Macumber Formation (Section 4.7). These abrupt changes could be explained by thrust duplications and solution-collapse of Macumber limestone strata.

5.3. Overprinting relationships of folds

Because of the continuous regional pattern and overprinting relationships observed, three distinctive generations of folds (F1, F2, F3) are interpreted as affecting Horton Group strata in the study area. Relative timing among different generation of structures can be established locally. There is no certainty on the relative time at regional scale (for example, F2 folds in Mutton Cove could have formed at a different time from the F2 folds in Little Rainy Cove or Walton).

Folds designated as F1 in Little Rainy Cove, Rainy Cove, and Walton are locally developed, highly disharmonic, occasionally ptygmatic and contain conspicuous convolute lamination (Section 3.5, 3.6, and 3.7). These folds appear variably oriented and refolded by later structures.

Folds designated as F2 folds are the most consistently present structures. F2 fold orientations indicate shortening in a northwest-southeast direction. Large-scale,

upright to overturned folds are tight to open, plunge moderately to the southwest and northeast, and display weak axial planar cleavage. Previous mapping by Johnston (1999) in the Cheverie area documented folds plunging to the northeast and southwest at the same scale as the folds recorded in this work. These folds are found throughout the coastal areas, from Cheverie to Walton. They are therefore designated F2 folds throughout the study area, even in areas where the F1 folds are not present.

Regional-scale folds overprint the F1 and F2 folds (Section 3.5, 3.6, and 3.7). These folds, designated F3, are tight, plunge gently to the southwest, and display variable amplitudes and wavelengths.

The distribution of bedding is, in general, a girdle oriented northwest-southeast (Fig. 5.2). Mutton Cove shows a cluster that could be contained in these girdles. In Little Rainy Cove, Rainy Cove, and Walton areas, the F2 folds display orientations and overprinting relationships different from the folds in the coast from Cheverie to Cambridge Cove. A change in orientation is observed in Little Rainy Cove, probably because of the interference between F2 and F3 folds. This interference is possibly the cause of dispersion of bedding girdles observed in Rainy Cove and Little Rainy Cove.

Cleavage planes are in general axial planar to the main F2 folds (Chapter 3). The distribution of cleavage in the study area is summarized in Fig. 5.3. The poles are distributed in a girdle oriented northwest-southeast. This means that, regionally, the interpreted cleavage surfaces S2 are folded about a mean F3 fold axis plunging to the southwest.

From Cheverie to Walton, the majority of the F2 fold hinges plunge to the northeast and southwest (Fig. 5.4). Most F2 hinges are spread along a subhorizontal girdle that strikes northwest-southeast, especially in Cheverie and Mutton Cove areas (Fig. 5.4 A and B). Folds in the Cheverie area are probably related to both dextral transpression and diapirism (Chapter 1 and 3) and therefore some of the recorded hinges are variably oriented. Major changes are observed in Little Rainy Cove and Rainy Cove (Fig. 5.4 E, F) due to a combination of F2 and F3 folds. The dispersion of F2 hinges cannot be fully interpreted in Rainy Cove (Fig. 5.4 F) because of alternative identifications of folds as F2 or F3 (Section 3.6.2).

Fig. 5.5 shows a regional interpretation of the relationship between F2 and F3 folds. The south shore of the Minas Basin represents a transpression zone where F2 folds occurred in an earlier stage than the F3 generation. Cheverie, Mutton Cove, Bass Creek, and Cambridge Cove areas display southwest-plunging F2 folds with axial traces oriented northeast-southwest. F2 folds in Little Rainy Cove also plunge to the southwest but show axial traces oriented northwest-southeast. Areas to the west of Little Rainy Cove are here interpreted as being part of an F3 limb. Little Rainy Cove would represent another F3 limb close to a major L3 hinge zone, i.e., Rainy Cove, where F3 folds can be observed in varied scales.

The orientation of the F3 folds in Rainy Cove and Walton is more east-west than the F2 folds. If the F3 folds are the result of the interpreted transpression, this observation indicates that the component of convergence was larger than the transcurrent component. Another possible mechanism of generation of the F3 folds is solution collapse of underlying evaporite. Since the subsurface data shows that

changes in thickness of the Macumber Formation are regionally extended, it is possible that major F3 folds were developed as collapse structures. The absence of axial planar cleavage to the F3 folds is possibly related to the mechanism of generation of these folds. If the F3 folds were generated as collapse structures, then no fabrics recording shortening would develop, since extension prevails during collapse.

5.4. Faults

The majority of the faults documented in the study area are thrust and reverse faults, although a minority of normal faults have been recorded in most areas. Reverse and thrust faults are generally oriented northeast-southwest and exhibit apparent offsets or stratigraphic throws of a few metres. In general, normal faults strike northwest-southeast and show apparent offsets of a few metres. Qualitatively, the northwest-southeast shortening accommodated by thrusts and reverse faults appears to be larger than the northeast-southwest elongation achieved through normal faults.

Faults with dextral strike slip component that strike northeast-southwest were documented in Mutton Cove, Bass Creek, Cambridge Cove, Little Rainy Cove, and Walton areas (Sections 3.2, 3.3, 3.4, 3.5, and 3.7, respectively). The flower structure documented at Mutton Cove shows that dextral transpression occurred at a local level (Section 3.2). These observations indicate that a regional dextral component of strike slip affected Carboniferous rocks.

The continuous, regional pattern of structures, especially F2 folds and cleavage, is consistent with northwest-southeast shortening and dextral strike-slip movement in an east-west direction. Local observations like strain markers in Cambridge Cove are consistent with northwest-southeast shortening (Section 3.4). The overall pattern of structures also indicates that dextral transpression occurred regionally.

Some structures are not obviously consistent with the proposed environment of dextral transpression. In Little Rainy Cove and Rainy Cove, reverse faults strike northwest-southeast. In these areas, F2 folds are overturned to downward-facing, and plunge moderately to steeply to the southwest. Progressive rotation and overprinting by the F3 folds could have determined the present-day orientation of the reverse faults and F2 folds in these areas.

The centre of the dextral transpression zone is inferred to lie north of the present coast. In the north shore of the Minas Basin, the Cobequid-Chedabucto fault system separates the Meguma Terrane of southern Nova Scotia (Carboniferous rocks) from the Avalon Terrane (pre-Carboniferous rocks) to the north (Section 1.1.1). In several subareas of this fault system, kinematic analysis of structures at outcrop and microscopic scales indicates dextral strike-slip movement (Eisbacher, 1969; Mawer and White, 1986). The present work supports the idea that the boundary between the Avalon and Meguma terranes is a transpressional boundary, resulting from oblique tectonics active in the Late Paleozoic.

5.5. Absolute timing

Regionally, absolute timing of the deformation cannot be established. Locally, in the Cheverie area (Section 1.2), folded Horton Bluff strata host a mafic dike that was dated ($^{40}Ar/^{39}Ar$ whole rock) at 315 ± 4 Ma (Johnston, 1999; Kontak et al., 2000). This dike disrupts a tectonic fabric in Horton shales. Therefore, the minimum age for the deformation of Horton Bluff rocks in the Cheverie area is Namurian-Westphalian (Johnston, 1999).

Palynological samples from the undeformed Scotch Village Formation from drill hole STY93-1 were taken by Boehner (1994). The age obtained was Westphalian. These results suggest that the deformation that affected the Horton Group occurred prior to the Westphalian.

5.6. Economic implications

Barite was the main product of the Walton Mine for about 40 years. The orebody was determined to be in the contact between the Windsor and the Horton groups (Hudgins, 1984). The area was explored for more than twenty years by several methods (gravimetry, drilling) but no additional economically profitable bodies were found.

Exploration in the present-day is targeted toward gold and base-metals disseminated in the Windsor Group. Gold was found in the Walton Mine disseminated in limestones of the Macumber Formation (O' Sullivan and Macfie, 1988). Limestones can be highly altered by epithermal fluids and result in high value

carbonate-hosted gold and silver deposits (Berger, 1992). The classic example of this type of deposit is Carlin, in Nevada, USA. The potential of the Macumber Formation as gold host is reduced in the area of study because of karst and solution-collapse phenomena. Abrupt changes in thickness and the high degree of uncertainty should be considered when planning future exploration.

Base-metals and manganese were exploited in Walton, Sturgis, and Lantz mines (Hudgins, 1984; Black, 1995), hosted in the Pembroke Breccia and the Macumber Formation. Exploratory drill holes are for now the only way to verify stratigraphic relations at shallow depths, where these minerals are found. Base-metals are associated with mafic dikes in Cheverie Mountain (Kontak et al., 2000). A careful revision of the exposed dikes and geophysical methods could illustrate the potential of these areas.

Gypsum of the White Quarry Formation has been mined for decades and some quarries are still active. Most of the area studied in this work has been explored by gravimetric methods. Associations between barite and gypsum were rarely found in drilling campaigns after the successful exploitation of the Walton Mine. Although there are outcrops of high-quality gypsum available and possibly unexposed, mining opportunities will be based in current prices and the cost of overburden removal. The existence of regional overthrust, tectonic windows, and releasing bends should be part of a new exploratory approach in the area.

Gas was registered in Well Cheverie-01 in the upper member of the Horton Bluff Formation (McDonald, 2001). Cutting logs from this interval revealed coarse-grained quartzitic sandstone that could correspond to the "glass sandstone" identified

by Moore (1996) as a marker bed in the upper member. These observations indicate that the upper member has potential as reservoir rock. Cheverie fine sandstones are well sorted and porous, and therefore can be regarded as possible reservoir rocks. Liquid petroleum has been reported in the Windsor Group, trapped in limestone breccia and anhydrite (McDonald, 2001), which can act as seal rocks.

Organic-rich black shales exist in the Lower and Middle members of the Horton Bluff Formation. Their potential as source rocks is not known. Based on results from three wells, it was concluded that the amount of oil contained in the Horton Group was not economical (McDonald, 2001). The Horton Bluff Formation, the Cheverie Formation, and the White Quarry Formation, can be regarded as a petroleum system in which the amount of oil and gas generated by the source rock and the efficiency of the seal are not well established.

5.7. Other possible models

Other models could be envisaged which will explain some of the field observations. The presence of salt domes and drag zones was established in Cape Breton Island by Alsop (2000). Structures of this type were interpreted in the Summerville area (Section 3.1). Hypothetically, large-scale evaporite domes located immediately offshore to the NW could produce large-scale drag folds with varied orientations. Salt domes are interesting hypothesis to explore but they cannot account for all of the field observations. The main F2 folds display a regular pattern that

would be difficult to produce by drag zones (typically chaotic areas). Also, most of the evaporite diapirs in the area occur at outcrop-scale.

A pure shear setting where the shortening would be oriented NW-SE could account for folds trending NE-SW. However, the presence of strike-slip faults running E-W and *en echelon* arrangements of the main folds in the coast suggest an important wrench component.

Similar orientations of the main structures would result from a dextral transtension oriented E-W or NE-SW. In this case, folds plunging to the NE and SW would develop in combination with NW-SE-striking normal faults. The development of cleavage surfaces and the predominance of reverse faults and other contractional structures contradict this hypothesis. The overprinting relationships observed along the coast are better explained in a dextral transpressional context.

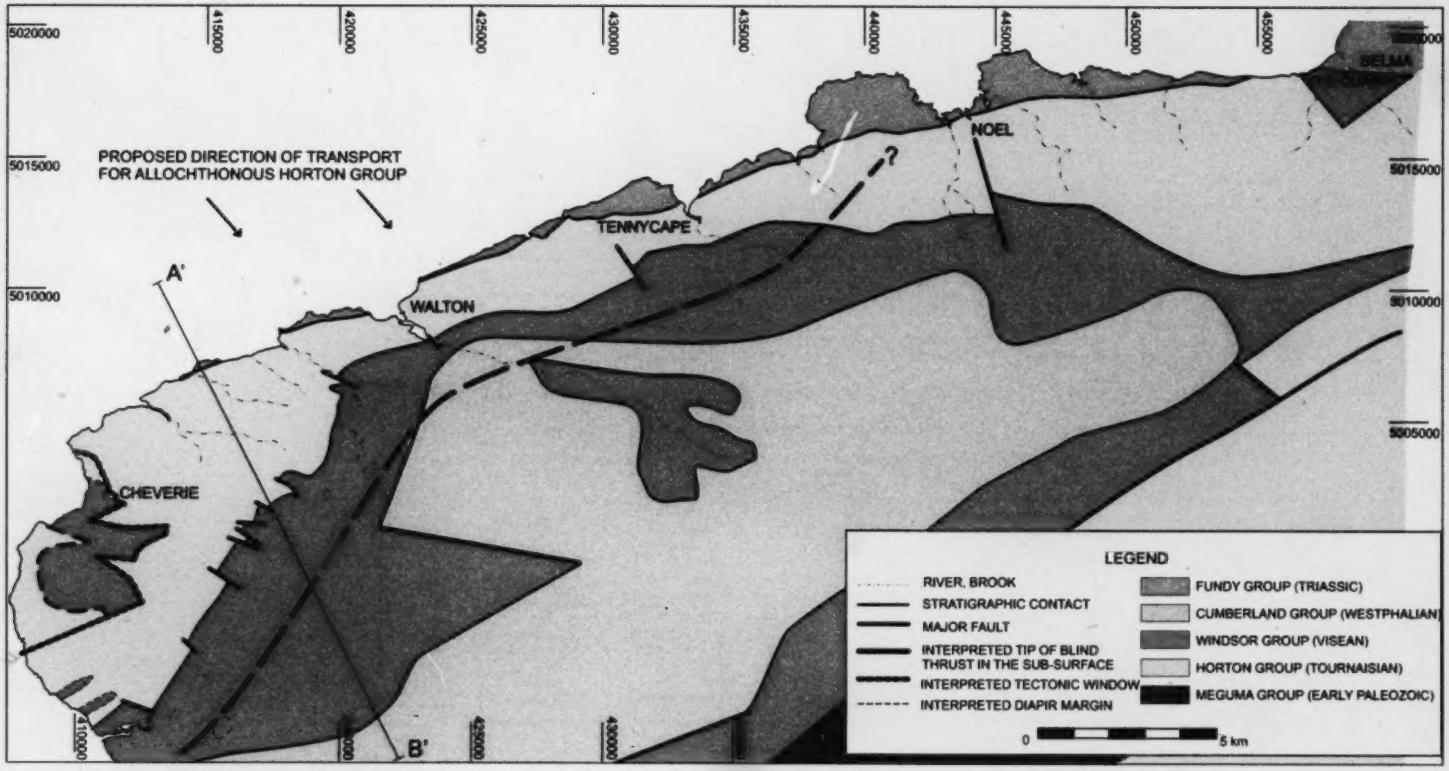


Figure 5.1: Regional interpretation of the study area: Geologic map showing the approximate southern limit of transported Horton Group. Evaporite diapirs and tectonic windows are also displayed. Cross-section A'B' is shown in Figure 5.2. Contacts were modified from Crosby (1962), Donohoe and Grantham (1989), and Moore et al. (2000).

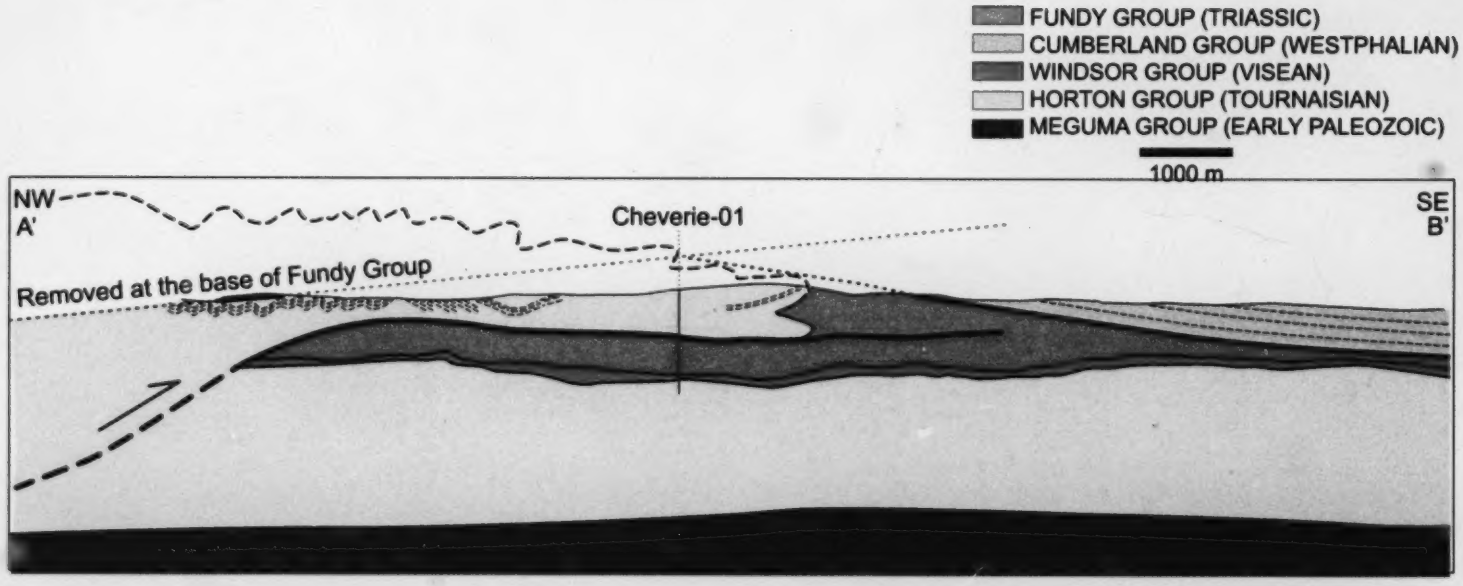


Figure 5.2: Cross-section A'B' of the study area (see Figure 5.1). Allochthonous Horton rocks transported southeastward on top of autochthonous Horton and Windsor evaporite. Gypsum and anhydrite of the White Quarry Formation provide a detachment surface. The thrust surface does not reach the surface; the thrust is, therefore, "blind". Recumbent folds appear near the hanging wall cutoff (based on drill hole cross-section of Walton Mine, see Figure 4.4). The plane of the cross-section is parallel to seismic section WND00-002 (see Figure 4.9); lithology logs from Cheverie-01 oil well, mining drill hole sections and seismic reflectors were employed.

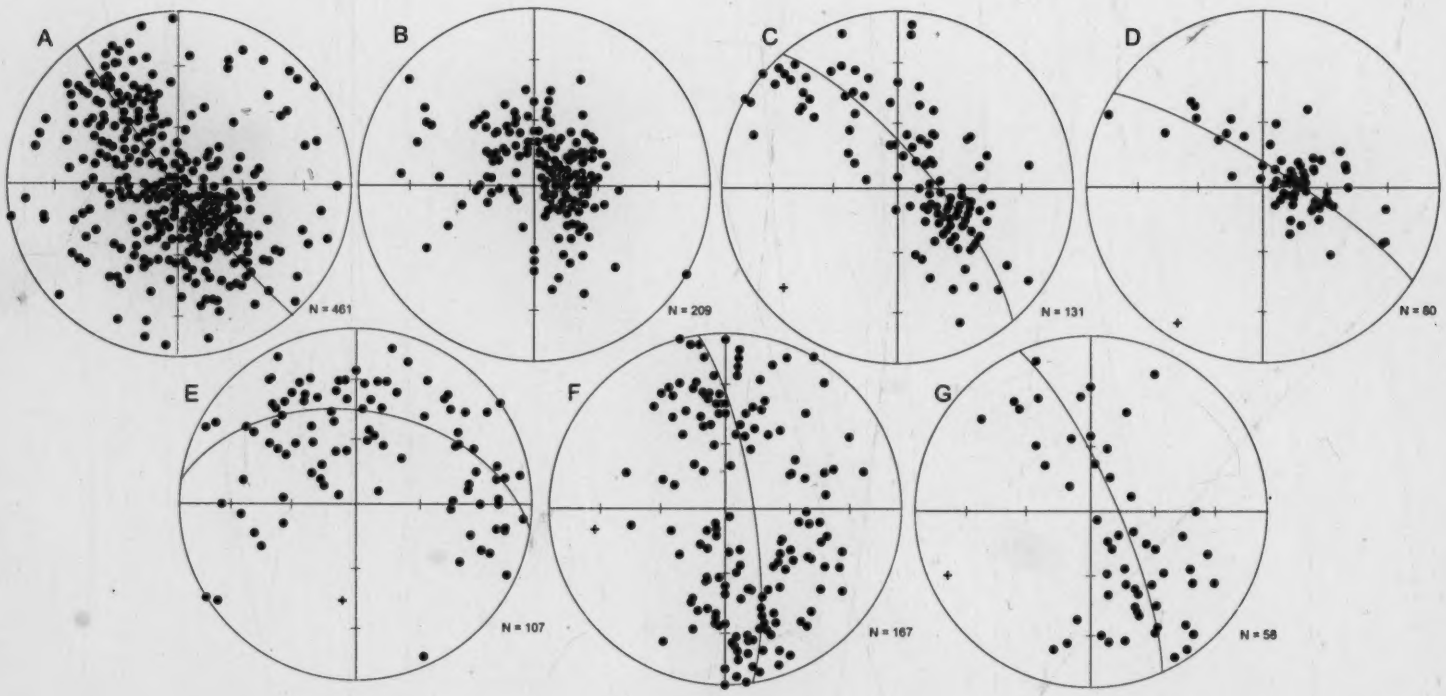


Figure 5.3: Comparative stereograms, poles to bedding. A) Cheverie (after Johnston, 1999); B) Mutton Cove; C) Bass Creek; D) Cambridge Cove; E) Little Rainy Cove; F) Rainy Cove; G) Walton. Most areas show girdle distributions about a southwest-plunging axis. Little Rainy Cove and Rainy Cove show dispersed girdle and changes in orientation, possibly due to fold interference.

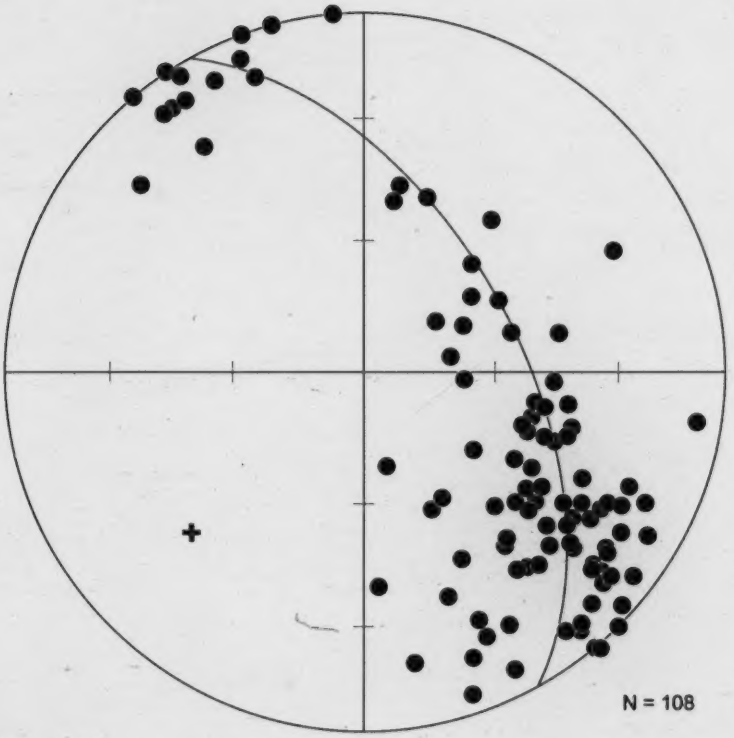


Figure 5.4: Poles to cleavage, from Cheverie to Walton. Girdle distribution (317/55) about a mean axis (227-35) indicates that cleavage in the study area is folded (Cheverie data after Johnston, 1999).

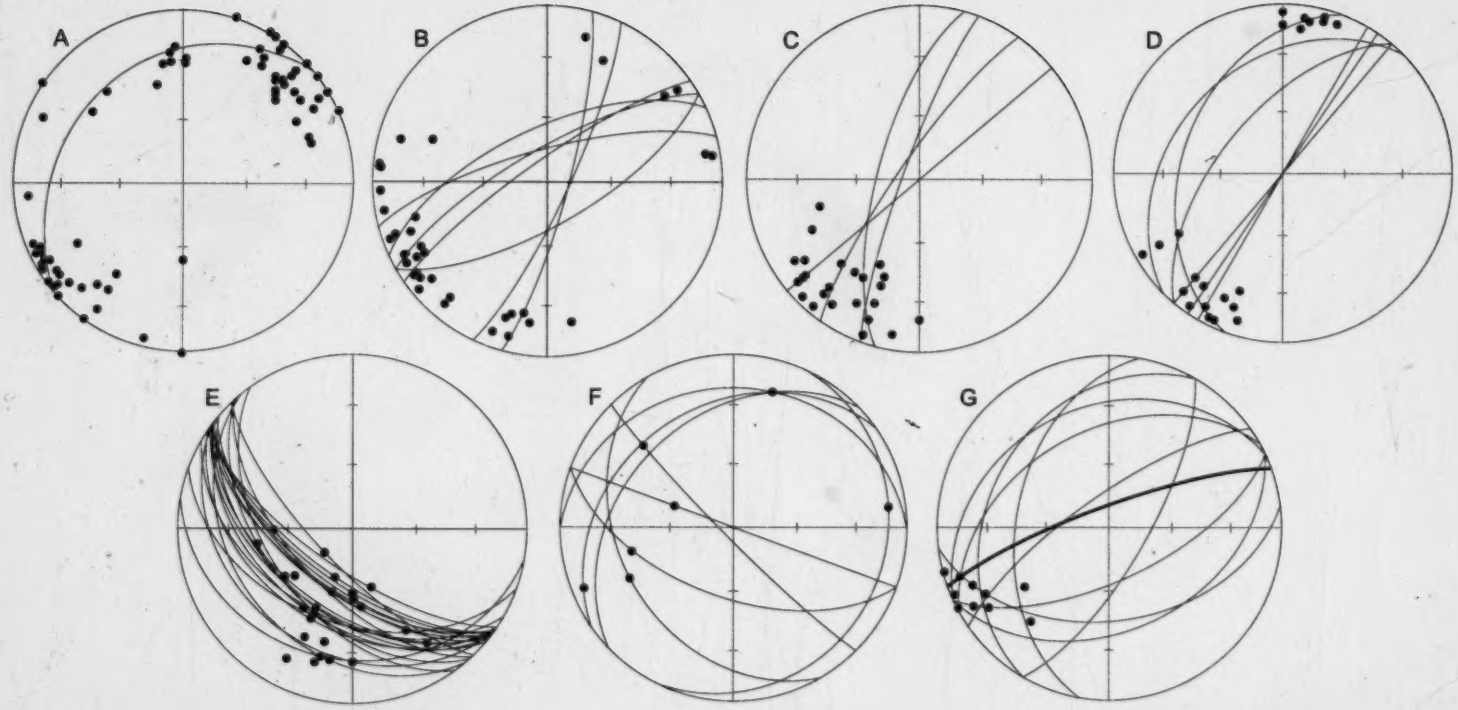


Figure 5.5: Comparative stereograms, hinges (dots) and axial surfaces of main folds (great circles). A) Cheverie (mean axial plane shown, after Johnston, 1999); B) Mutton Cove; C) Bass Creek; D) Cambridge Cove; E) Little Rainy Cove; F) Rainy Cove; G) Walton (F3 axial surface in bold). F2 folds plunge to the southwest except in Rainy Cove, due to a combination of F2 and F3. F2 hinges appear spread, possibly because of interference with large-scale F3 folds.

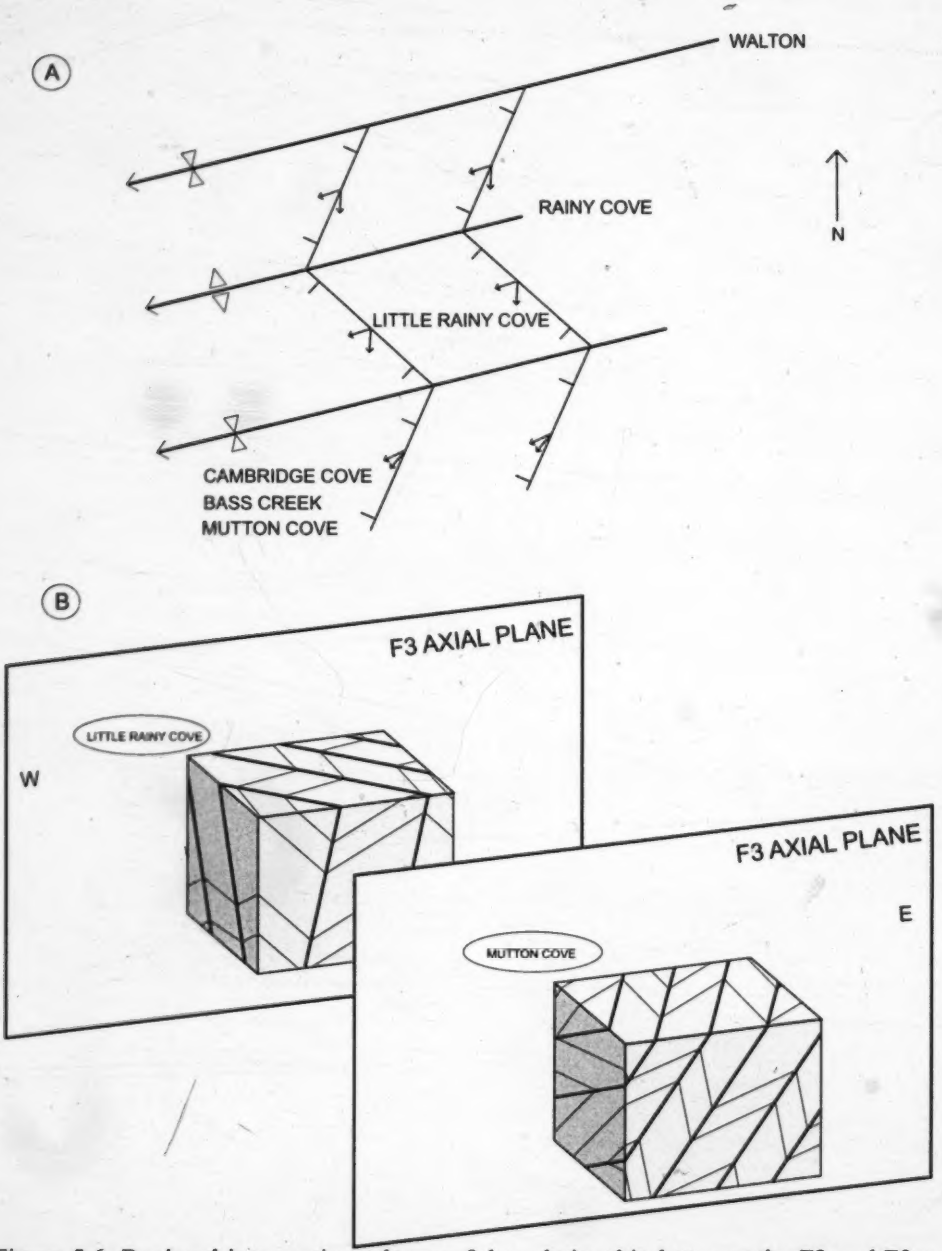


Figure 5.6: Regional interpretive scheme of the relationship between the F2 and F3 folds. A) Plan view of F2 (light) and F3 (bold) axial traces. Average recorded L2 hinges are shown in fine arrows. Inclination of the F2 axial planes is also displayed. The F3 folds plunge to the southwest (arrows). B) Block diagrams showing the trace of bedding (light) and its relationship with F2 and F3 axial planes (bold). F2 axial planes are folded, striking northeast-southwest in the south limb of F3, and northwest southeast in the north limb.

6. Conclusions

The Horton Group is highly deformed in the coast from Mutton Cove to Lower Selma and in the Summerville area. Most of the mapped folds, faults and fabrics in the Horton Bluff Formation are consistent with a dextral transpressional zone that strikes east-northeast to west-southwest. The boundary between the Meguma and Avalon terranes is here reinterpreted as a transpressional boundary.

There are at least three generations of folds (F1, F2, F3) affecting the Horton Group, identified on the basis of their overprinting relationships. The F2 folds are related to the proposed dextral transpression. The F3 folds were interpreted as (1) related to the dextral transpression, developed in a setting where shortening was dominant over transcurrence; and (2) unrelated to the dextral transpression, probably the result of solution-collapse of underlying Windsor limestone.

Mapped outcrops, mining drill holes, oil wells, and interpreted seismic sections, indicate that part of the Horton Group has been thrusted on top of the Windsor Group. The Horton Bluff Formation has been identified in the area by palynological and sedimentologic characteristics. One or more thrust surfaces probably exist, and shallow nappes are inferred to be associated with the main thrust.

The evaporites of the White Quarry Formation could have acted as a detachment surface for the inferred regional thrust. Evaporite diapir probably developed after the thrust took place, affecting also the overlying allochthonous Horton Group.

Major changes in thickness of the Macumber Formation found at depth are the result of solution-collapse of limestones. The Pembroke Breccia is here interpreted as a karstic breccia resulting from the dissolution and collapse of upper limestone layers of the Macumber Formation. These phenomena probably affected overlying strata and generated the F3 folds in the Horton Group.

Further efforts in oil and gas exploration should take into consideration the presence of petroleum systems.

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Utting, J. 2002 (b). Palynological examination of 6 subsurface samples from Cheverie Mountain Well (Cheverie-01), Nova Scotia. Geological Survey of Canada Paleontological Report 8-JU-2002 (unpublished).

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Appendix 1: Palynology Reports

4-JU-2002

PALYNOLOGICAL EXAMINATION OF 1 OUTCROP SAMPLE FROM WALTON, NOVA SCOTIA, SUBMITTED BY J. WALDRON, UNIVERSITY OF ALBERTA, EDMONTON, ALBERTA

LOCALITY:
Coastal section near Walton
GSC locality number: C-412950
Field number: HA 011
UTM 20T
Northing 5007991
Easting 415915
Rock type: grey mudstone and siltstone.

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Coaly fragments subangular to subrounded (abundant); woody fragments (common); exinous fragments (rare); finely dispersed organic debris (rare).
Preservation of spores:
Rare dark spores are poorly preserved. Exines corroded by growth of sulphide pseudomorphs.
Thermal maturity:
TAI 3+ to 4-; equivalent to vitrininte reflectance value of (Ro)% 1.8 (dry gas generation zone).

IDENTIFICATIONS (number of specimens given in parentheses):
The identifications given below are tentative due to the poor preservation.
Knoxisporites sp.(1), *Kraeuselisporites echinatus* Owens, Mischell and Marshall 1976 (7), *Potonieisporites/Florinites* spp. complex (3), *Punctatisporites* sp.(1) and *Verrucosisporites* sp. (1).

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION:

The association of *Kraeuselisporites echinatus* and the *Potonieisporites/Florinites* spp. complex indicates an age no older than early Namurian i.e. no older than the Mabou Group. It is possible that further sampling would enable a more precise age to be obtained.

No marine palynomorphs were seen indicating a terrestrial environment of deposition. The common sulphide pseudomorphs suggest anoxic conditions at the sediment water interface.

REFERENCE:

Utting, J., Goodarzi, F., Dougherty, B.J. and Henderson, C.M. (1989) Thermal maturity of Carboniferous and Permian rocks of the Sverdrup Basin, Canadian Arctic Archipelago, Geological Survey of Canada, Paper 89-19: 20p.

John Utting
Paleontology Subdivision
Geological Survey of Canada (Calgary)
Calgary, 2002-3-18

7-JU-2002

PALYNOLOGICAL EXAMINATION OF 9 OUTCROP SAMPLE FROM NOVA SCOTIA, SUBMITTED BY J. WALDRON, UNIVERSITY OF ALBERTA, EDMONTON, ALBERTA

The relevant parts of any manuscript prepared for publication that paraphrase or quote from this report should be referred to the author or, if not available, the Chief Paleontologist, Geological Survey of Canada, Calgary for possible revision.

All references to age determination and paleontological data must quote the authorship of the report, GSC, Calgary report number and the unique GSC locality number of the fossil collection.

INTRODUCTION:

The aim of the study was to determine the age of the samples, the environment of deposition, and thermal maturity. The Thermal Alteration Index (TAI) is assessed from spore colouration previous to oxidation treatment, and the values thus obtained may be correlated with vitrinite reflectance (Utting et al., 1989). Approximate proportions of organic matter given in this report are based on visual estimates made prior to oxidation or filtration of the organic residue.

LOCALITY:

Windsor Area
GSC locality number: C-405777
Field number: HM 004
UTM zone 20
Easting 415915
Northing 5007991

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:
Coaly fragments small, medium and large, subangular to angular (common); woody fragments (common); exinous fragments (rare); finely dispersed organic debris (abundant).
Preservation of spores:
Poor. Exines corroded by growth of pseudomorphs some of which are rhombic in shape.
Thermal maturity:
TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:
Grandispora uncata (Hacquebard) Playford, *Spelaeotriletes cabotii* Utting, *Vallatisporites vallatus* Hacquebard, *Vallatisporites verrucosus* Hacquebard

GSC locality number: C-405778
Field number: HM 005
UTM zone 20
Easting 404490
Northing 4994280

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Coaly fragments small, medium and large, subangular to angular (common); woody fragments (common); exinous fragments (rare); finely dispersed organic debris (abundant).
Preservation of spores:
Poor. Exines corroded by growth of pseudomorphs some of which are rhombic in shape.
Thermal maturity:
TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:
Apiculatisporis heteroconus Phillips and Clayton, *Acanthotriletes acritarchus* Neville, *Grandispora uncata, Punctatisporites glaber* (Naumova) Playford, *Raistrickia clavata* Hacquebard emend. Playford , *Schopfites delicatus* Higgs, *Schopfites augustus* Playford, *Spelaeotriletes cabotii* Utting (abundant), *Vallatisporites vallatus* Hacquebard, *Vallatisporites verrucosus* Hacquebard, *Vallatisporites* sp.

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION FOR C-40577-8:
The association of *V. vallatus,* and *S. cabotii* correlates with the *S. cabotii* subzone of the *V. vallatus* Assemblage Zone of Utting et al. (1989). This sub-zone was assigned to the upper Courceyan (upper Tournaisian) which suggests a correlation with the upper middle to upper Horton Bluff Formation. No marine palynomorphs were seen possibly indicating a terrestrial environment of deposition. The common rhombic pseudomorphs may have formed due to dolomitisation at the time of deposition, or subsequently during diagenesis.

LOCALITY:
Bramber Area
GSC locality number: C-405779

Field number: HM 006
UTM zone 20
Easting 408634
Northing 5004616

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Coaly fragments subcircular to subangular (common); woody fragments (common); exinous fragments (rare).

Preservation of spores:
Very poor. Exines corroded by growth of pseudomorphs some of which are rhombic in shape.
Thermal maturity:
TAI 4; equivalent to vitrinite reflectance value of (Ro)% 2.4 (dry gas generation zone).

IDENTIFICATIONS:
Some circular black entities that are probably carbonised spores.

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION:
Not determined.

LOCALITY:
Johnson Cove N
GSC locality number: C-405780
Field number: HM 007
UTM zone 20
Easting 408311
Northing 5003373

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Rare coaly and woody fragments; rare finely dispersed organic debris.
No palynomorphs or exinous fragments.

LOCALITY:
Johnson Cove S
GSC locality number: C-405781
Field number: HM 008
UTM zone 20

Easting 408218
Northing 5003480

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Coaly and woody fragments; rare exinous fragments.
Rare unidentifiable spores
Thermal maturity:
TAI 4; equivalent to vitrinite reflectance value of (Ro)% 2.4 (dry gas generation zone).

LOCALITY:
Tennycape Area
GSC locality number: C-405782
Field number: HM 009
Easting 431551
Northing 5012969

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Coaly fragments small, medium and large, subangular to angular (abundant); woody fragments (abundant); exinous fragments (rare).
Preservation of spores:
Poor. Exines corroded by growth of pseudomorphs some of which are rhombic in shape.
Thermal maturity:
TAI 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:
Raistrickia clavata Hacquebard, *Spelaeotriletes cabotii, Vallatisporites vallatus, Vallatisporites verrucosus*

GSC locality number: C-405783
Field number: HM 009
UTM zone 20
Easting 431551
Northing 5012969

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular (abundant); woody fragments (abundant); exinous fragments (rare).

Preservation of spores:

Poor. Exines corroded by growth of pseudomorphs some of which are rhombic in shape.

Thermal maturity:

TAI 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Cyclogranisporites commodus Playford, *Raistrickia clavata, Spelaeotriletes cabotii, Vallatisporites vallatus* (abundant), *Vallatisporites verrucosus.*

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION:

The association of *V. vallatus,* and *S. cabotii* correlates with the *S. cabotii* subzone of the *V. vallatus* Assemblage Zone of Utting et al. (1989). This sub-zone was assigned to the upper Courceyan (upper Tournaisian) which suggests a correlation with the upper middle to upper Horton Bluff Formation.No marine palynomorphs were seen possibly suggesting a terrestrial environment of deposition. The common rhombic pseudomorphs may have formed due to dolomitisation at the time of deposition, or subsequently during diagenesis.

LOCALITY:

Pembroke Area
GSC locality number: C-405784
Field number: HM 011
UTM zone 20
Easting 415947
Northing 5007944

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular (abundant); woody fragments (abundant); exinous fragments (rare).

Preservation of spores:

Very poor. Exines corroded by growth of pseudomorphs some of which are rhombic in shape.

Thermal maturity:

TAI 3+/4-; equivalent to vitrinite reflectance value of (Ro)% 1.8 (dry gas generation zone).

IDENTIFICATIONS:
Apiculatisporis ? sp., *Crassispora trychera* Neves and Ioannides, *Raistrickia ponderosa* Playford, *Spelaeotriletes cabotii.*

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION:
The presence of *S. cabotii* indicates an age no older than the *S. cabotii* subzone of the *V. vallatus* Assemblage Zone of Utting et al. (1989). It may be younger, but the lack of *Lycospora* suggests it is pre-Viséan.
No marine palynomorphs were seen possibly suggesting a terrestrial environment of deposition. The common rhombic pseudomorphs may have formed due to dolomitisation at the time of deposition, or subsequently during diagenesis.

LOCALITY:
Coastal section near Walton
GSC locality number: C-412950
Field number: HA 011
UTM 20T

Easting 415915
Northing 5007991
Rock type: grey mudstone and siltstone.

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:
Organic matter:
Coaly fragments subangular to subrounded (abundant); woody fragments (common); exinous fragments (rare); finely dispersed organic debris (rare).
Preservation of spores:
Rare dark spores are very poorly preserved. Exines corroded by growth of rhombic pseudomorphs.
Thermal maturity:
TAI 3+; equivalent to vitrininte reflectance value of (Ro)% 1.7 (dry gas generation zone).

IDENTIFICATIONS:
The tentative identifications given in the previous report (4-JU-202) were based on very poorly preserved specimens in a single sample. Further work on this sample yielded rare, but identifiable, slightly better preserved specimens listed below.

Apiculatisporis sp., *Grandispora uncata, Discernisporites micromanifestus* (Hacquebard) Sabry and Neves, *Vallatisporites vallatus.*

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION:

No precise age determination is possible, but the association of *Grandispora uncata, Discernisporites micromanifestus, Vallatisporites vallatus* suggest a Tournaisian age i.e. Horton Group. No marine palynomorphs were seen possibly indicating a terrestrial environment of deposition. The common rhombic pseudomorphs may have formed due to dolomitisation at the time of deposition, or subsequently during diagenesis.

REFERENCES:

Utting, J., Goodarzi, F., Dougherty, B.J. and Henderson, C.M. (1989) Thermal maturity of Carboniferous and Permian rocks of the Sverdrup Basin, Canadian Arctic Archipelago, Geological Survey of Canada, Paper **89-19**: 20p.

Utting, J., Keppie, J.D. and Giles, P.S.(1989b) Palynology and stratigraphy of the Lower Carboniferous Horton Group, Nova Scotia. In Contributions to Canadian Paleontology,Geological Survey of Canada , Bulletin **396**, p. 117-143.

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Geological Survey of Canada (Calgary)
2002-05-28

A. Sweet
Chief Paleontologist GSC(C)

8-JU-2002

PALYNOLOGICAL EXAMINATION OF 6 SUBSURFACE SAMPLES FROM THE CHEVERIE MOUNTAIN WELL (CV01), NOVA SCOTIA, SUBMITTED BY J. WALDRON, UNIVERSITY OF ALBERTA, EDMONTON, ALBERTA

The relevant parts of any manuscript prepared for publication that paraphrase or quote from this report should be referred to the author or, if not available, the Chief Paleontologist, Geological Survey of Canada, Calgary for possible revision.

All references to age determination and paleontological data must quote the authorship of the report, GSC, Calgary report number and the unique GSC locality number of the fossil collection.

INTRODUCTION:

The aim of the study was to determine the age of the samples, the environment of deposition, and thermal maturity. The Thermal Alteration Index (TAI) is assessed from spore colouration previous to oxidation treatment, and the values thus obtained may be correlated with vitrinite reflectance (Utting et al., 1989). Approximate proportions of organic matter given in this report are based on visual estimates made prior to oxidation or filtration of the organic residue.

WELL LOCATION:

Cheverie Mountain CV01.
UTM zone 20 T, 5002880 N ; 414876 E.
NAD 27 datum 45.17622; -64.083329

GSC LOCALITY NUMBER C-405797:

Depth: 30-35 m

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:
Coaly fragments small, medium and large, subangular to sub-rounded, and woody fragments (dominant); exinous fragments (rare); finely dispersed organic debris (rare).

Preservation of spores:
Poor. Exines often corroded by growth of sulphide pseudomorphs.

Thermal maturity:
TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Crassispora trychera Neves and Ioannides, *Grandispora uncata* (Hacquebard) Playford, *Spelaeotriletes pretiosus* var. *pretiosus* (Playford) Utting, *Vallatisporites vallatus* Hacquebard, and *Vallatisporites verrucosus* Hacquebard.

GSC LOCALITY NUMBER: C-405798

Depth: 110-115 m

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular and woody fragments (dominant); exinous fragments (rare).

Preservation of spores:

Poor. Exines corroded by growth of sulphide pseudomorphs.

Thermal maturity:

TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Crassispora trychera, Discernisporites micromanifestus (Hacquebard) Sabry and Neves, *Raistrikia clavata* Hacquebard, *R. ponderosa* Playford, *Schopfites claviger* Sullivan, *Spelaeotriletes pretiosus* var. *pretiosus*, and *Vallatisporites verrucosus* Hacquebard.

GSC LOCALITY NUMBER: C-405799

Depth: 285-290 m

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular and woody fragments (dominant); exinous fragments (rare).

Preservation of spores:

Poor. Exines corroded by growth of sulphide pseudomorphs.

Thermal maturity:

TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Auroraspora macra Sullivan, Punctatisporites planus Hacquebard, *Spelaeotriletes pretiosus* var. *pretiosus* (common), *Vallatisporites verrucosus* Hacquebard.

GSC LOCALITY NUMBER: C-405800

Depth: 45.0-45.5 m

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular and woody fragments (rare to common); finely dispersed organic debris (dominant).

Preservation of spores:

Very poor. Exines corroded by growth of sulphide pseudomorphs.

Thermal maturity:

TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Crassispora trychera and *Punctatisporites planus.*

GSC LOCALITY NUMBER: C-405801

Depth: 575-580 m

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular and woody fragments (dominant), exinous fragments (rare).

Preservation of spores:

Very poor. Exines corroded by growth of sulphide pseudomorphs.

Thermal maturity:

TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Crassispora trychera and *Vallatisporites vallatus.*

GSC LOCALITY NUMBER: C-405802

Depth: 805-810 m

ORGANIC MATTER, PRESERVATION OF SPORES, AND THERMAL MATURITY:

Organic matter:

Coaly fragments small, medium and large, subangular to angular and woody fragments (dominant), exinous fragments (rare).

Preservation of spores:

Very poor. Exines corroded by growth of sulphide pseudomorphs.

Thermal maturity:

TAI 3 to 3+; equivalent to vitrinite reflectance value of (Ro)% 1.5 (dry gas generation zone).

IDENTIFICATIONS:

Anapiculatisporites hystricosus Hacquebard, *Crassispora trychera, Punctatisporitser planus, Spelaeotriletes cabotii* Utting, *Vallatisporites vallatus* (common), and *V. verrucosus.*

PROBABLE AGE AND ENVIRONMENT OF DEPOSITION:

In spite of the poor preservation sufficient taxa are identifiable to provide an approximate age determination. In samples C-405797 to C-405801 the relative common occurrence of *S. pretiosus* var. *pretiosus (*in C-405799) suggests a correlation of the 30 - 580 m interval with the *S. pretiosus* var. *pretiosus* Assemblage Zone typically found in the Cheverie Formation of late Courceyan, late Tournaisian age (Utting et al., 1989).

In sample C-405802 the common occurrence of *V. vallatus* in association with *S. cabotii* suggests a correlation of the 805 - 810 m interval with the *S. cabotii* subzone of the *V. vallatus* Assemblage Zone of Utting et al. (1989). This subzone is of late Courceyan (late Tournaisian) age, and is typically found in the upper middle to upper Horton Bluff Formation.

No marine palynomorphs were seen in any of the samples, possibly indicating a terrestrial environment of deposition. The common sulphide pseudomorphs suggest anoxic conditions at the sediment water interface. The lack of rounded coaly fragments indicates only limited transport in water prior to deposition.

The relatively high thermal maturity suggests that the organic matter is in the dry gas generation one.

REFERENCES:

Utting, J., Goodarzi, F., Dougherty, B.J. and Henderson, C.M. (1989) Thermal maturity of Carboniferous and Permian rocks of the Sverdrup Basin, Canadian Arctic Archipelago, Geological Survey of Canada, Paper **89-19**: 20p.

Utting, J., Keppie, J.D. and Giles, P.S.(1989b) Palynology and stratigraphy of the Lower Carboniferous Horton Group, Nova Scotia. In Contributions to Canadian Paleontology,Geological Survey of Canada , Bulletin **396**, p. 117-143.

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2002-08-14